FINAL REPORT

Robotic Laser Coating Removal System

ESTCP Project WP-0526

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14. ABSTRACT
Oklahoma City Air Logistics Center, Headquarters Air Force Material Command, and the Air Force Research Laboratory performed the Robotic Laser Coating Removal System program to demonstrate and validate a RLCRS as an alternative technology to the current chemical and mechanical methods that are used to remove coatings from large off-equipment aircraft components at Tinker Air Force Base, OK. This project demonstrated the ability of this technology to meet the requirements for coatings removal in a production environment as well as the pollution reduction that can be achieved through its use across the Department of Defense. The RLCRS system was designed to accommodate processing of large parts that are currently subjected to coatings removal operations once they are removed from the airframe. This is the Final Report documenting the project results.

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ACRONYMS

AFB	Air Force Base
AFIOH	Air Force Institute for Operational Health
AFOSH	Air Force Occupational Safety and Health
AFRL	Air Force Research Laboratory
ALC	Air Logistic Center
ANSI	American National Standards Institute
CAA	Clean Air Act
CFR	Code of Federal Regulations
CO	Carbon monoxide
CO_2	Carbon dioxide
COTS	Commercial-off-the-shelf
CTC	Concurrent Technologies Corporation
CWA	Clean Water Act
DoD	Department of Defense
ECAM	Environmental Cost Analysis Methodology
EHS	Environmental Health and Safety
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
HAP	Hazardous Air Pollutants
He	Helium
HQ AFMC	Headquarters Air Force Materiel Command
IRR	Internal Rate of Return
JTP	Joint Test Protocol
JTR	Joint Test Report
LARPS	Large Area Robotic Paint Stripping
LASER	Light Amplification by Stimulated Emission of Radiation
LHMEL	Laser Hardened Materials Evaluation Laboratory
MPE	Maximum Permissible Exposure
N_2	Nitrogen
NASA	National Aeronautics and Space Administration
NDI	Non-Destructive Inspection
Nd:YAG	Yttrium Aluminum Garnet Crystals Doped with Neodymium Ions
NHZ	Nominal Hazard Zone
NOHD	Nominal Ocular Hazard Distance
NPV	Net Present Value
OC-ALC	Oklahoma City Air Logistics Center
OD	Optical Density
OEL	Occupational Exposure Limit
OMB	Office of Management and Budget
OSHA	Occupational Safety & Health Administration
PLCRS	Portable Handheld Laser Small Area Supplemental Coating Removal System
RCRA	Resource Conservation and Recovery Act
RFP	Request for Proposal
RLCRS	Robotic Laser Coatings Removal System
SERDP	Strategic Environmental Research and Development Program
TEA	Transversely Excited At Atmospheric Pressure

TRI	Toxics Release Inventory
UDRI	University of Dayton Research Institute
USAF	United States Air Force
VOC	Volatile Organic Compounds
WPAFB	Wright Patterson Air Force Base

LIST OF UNITS

°F	Degree(s) Fahrenheit
%IACS	Percentage of International Annealed Copper Standard
µm	Micrometer(s)
cm	Centimeter(s)
ft	Feet
ft^2-mil/min	Square feet per minute per mil of coating removed
in	Inch(s)
in-lb_f/in	Inch-pound(s) force per inch
J/cm^2	Joule(s) per square centimeter
ksi	Kip(s) per square inch
kW	Kilowatt(s)
lb_f	Pound(s) force
m	Meter(s)
m/s	Meter(s) per second
mrad	Milliradian(s)
mils	Thousandths of an inch (0.001 inches)
min	Minute(s)
mm	Millimeter(s)
nm	Nanometer(s)
psig	Pounds per square inch gauge
s	Second(s)
scfm	Standard cubic feet per minute
W	Watt(s)

ABSTRACT

Current methods for the removal of Department of Defense (DoD) coating systems from on-equipment and off-equipment components are costly, time consuming, labor-intensive, and result in undesirable environmental conditions. Large quantities of hazardous waste are commonly generated from these depot-related activities, and are typically subjected to high disposal costs and scrutiny under environmental regulations. The wastes that are associated with coatings removal include the disposal of liquid paint removers and contaminated rinse water from chemical stripping operations and media waste from a variety of blasting processes. Chemical paint removers are the only process currently authorized for removing paint from KC-135 aircraft and components. In 2007, Tinker AFB reported using approximately 4,360 gallons of chemical paint removers and generated approximately 2.7 million gallons of contaminated rinse water from the stripping of KC-135 candidate components alone.

Coatings removal activities are impacted by a number of regulations promulgated under the Clean Water Act (CWA), Clean Air Act (CAA), and Resource Conservation and Recovery Act (RCRA). Washing surfaces following depainting operations can generate quantities of wastewater contaminated with methylene chloride or media and paint residue. Discharging wastewater with traces of hazardous waste can result in a direct violation of the CWA. The most common regulations associated with depainting activities are those issued under the CAA, including the recent efforts to minimize the use of hazardous air pollutants (HAPs) such as methylene chloride. The RCRA directly regulates disposal of wastes generated by depainting activities. The RCRA regulates how and where depainting waste can be disposed and transported as well as any future liabilities resulting from environmental damage.

Because of these environmental concerns, all branches of the DoD that are currently involved in coatings removal operations are concerned with the identification of alternative methodologies that are focused primarily towards the elimination or reduction of chemical paint strippers, dry media blasting, and hand sanding. As a result, the Robotic Laser Coating Removal System (RLCRS) has been identified as an alternative technology to the current chemical and mechanical methods that are used to remove coatings from large off-equipment aircraft components at the Air Logistics Centers (ALCs).

The RLCRS is system that integrates advanced laser coating removal technology with an automated robotic system. The individual components of the RLCRS include the laser, robotic base, beam delivery system, laser scanner, and waste extraction systems. The use of laser paint stripping systems is applicable to depainting activities on large off-aircraft components and weapons systems for the Air Force, Army, Navy, Marine Corps, and National Aeronautics and Space Administration (NASA).

In this Environmental Security Technology Certification Program (ESTCP) project, design, assembly, and debugging of this system was performed at Concurrent Technologies Corporation (*CTC*) in Johnstown, Pennsylvania. Following debugging at *CTC*, a demonstration of this system was performed at the Oklahoma City Air Logistics Center (OC-ALC) at Tinker Air Force

Base (AFB), Oklahoma City, Oklahoma. The objective of this demonstration was to verify the ability of a robotic laser coating removal system to meet the requirements for coatings removal in a production environment without causing physical damage to the substrate. A second objective of this demonstration was to validate the pollution reduction that could be achieved through use of laser coating removal systems across the DoD.

This project built on previous Strategic Environmental Research and Development Program (SERDP) projects PP-139 "Laser Cleaning and Coatings Removal" and PP-134 "Large Area Robotic Paint Stripping (LARPS)" which were undertaken to automate the coatings removal process. Available documentation for these projects was reviewed and personnel involved in the projects were interviewed to gain an understanding of the technical difficulties encountered and to gather lessons learned in order to develop a sound technical approach to help ensure successful completion of this project. Process engineers from OC-ALC who worked on the LARPS system have been directly involved in every step of the development of the RLCRS system design. The primary obstacle identified with the LARPS system was the path programming to guide the water strip head across the aircraft surface. To help overcome this and other related technical challenges a team of industry leaders in robotic motion controls and systems integration, laser optics, beam delivery systems, lasers and laser depainting were assembled to assist with development of the RLCRS system.

The demonstration showed that the RLCRS is feasible for coating removal from large off-aircraft parts, to include, but not limited to, KC-135 ailerons, rudders, landing gear doors, elevators, and flaps. Almost all wastes associated with the current chemical removal process would be eliminated by the implementation of this technology. The only wastes that remain are the removed coating itself which is captured in filters, waste water from rinsing the parts after coating removal, and minor masking materials and personal protective equipment (PPE) (i.e., aluminum tape, cotton gloves, and wipes).

The cost benefit analysis showed that the implementation of the RLCRS results in a labor savings of approximately $7,400,000, an annual materials cost savings of approximately $113,600, and a waste management cost avoidance of approximately $60,000. The total annual operating cost savings equals approximately $7,500,000. A life cycle cost analysis demonstrated that implementation and use of the RLCRS for coating removal of the targeted KC-135 parts would result in 15-year life cycle cost savings greater than $111,000,000. These cost savings translate into a payback period of approximately 0.3 years.

It is estimated that other Air Force depot facilities, as well as other DoD facilities, that perform chemical depainting of large off-aircraft parts will also realize similar cost savings. For example, if similar cost savings were assumed at all three of the major Air Force depots that perform chemical depainting operations on aircraft parts, the combined cost estimates would result in labor savings of approximately $66,600,000, an annual materials cost savings of approximately $1,000,000, and an annual waste management cost avoidance of approximately $540,000. The total annual operating cost avoidance would result in approximately $67,000,000 per year for the United States Air Force (USAF).

1.0 INTRODUCTION

1.1 Background

Current methods for the removal of Department of Defense (DoD) coating systems from on-equipment and off-equipment components are costly, time consuming, labor-intensive, and result in undesirable environmental conditions. The chemicals that are typically used in this process are also high in volatile organic compounds (VOC) and hazardous air pollutants (HAP), both of which are targeted for reduction/elimination by environmental regulations. Coatings removal operations that use abrasive blast media instead of chemical methods result in large quantities of hazardous waste. This waste is subject to high disposal costs and scrutiny under environmental regulations.

A Robotic Laser Coating Removal System (RLCRS) has been identified as an alternative technology to the current chemical and mechanical methods that are used to remove coatings from large off-equipment aircraft components at the Air Logistic Centers (ALCs). A laser is a device that generates monochromatic, coherent light that can be focused and concentrated into a narrow, intense beam of energy. Lasers are currently used in multiple manufacturing operations, including welding, cutting, drilling, and surface treatment. The use of laser energy to strip coatings is a relatively new technology developed primarily for the aerospace industry.

Laser coating removal is a non-intrusive, non-kinetic energy process that can be applied to a variety of substrates, including composites, glass, metal, and plastics. The high level absorption of energy at the surface of a coating material results in the decomposition and removal of the coating. The applied energy is mostly absorbed and utilized in coating decomposition (i.e., instant evaporation, which carries away most of the radiation energy); therefore, the substrate experiences only a minimal increase in temperature.

1.2 Objectives of the Demonstration

The objective of this demonstration was to verify the ability of a robotic laser coating removal system to meet the requirements for coatings removal in a production environment without causing physical damage to the substrate, as well as the pollution reduction that can be achieved through its use across the DoD. After successfully demonstrating this new technology on test panels and actual aircraft components, the robotic system will be transitioned to an aircraft depot for production use.

While the project is based on an existing Strategic Environmental Research and Development Program (SERDP) gantry-style robot, the ultimate goal is not to design a one-of-a-kind system usable on only one specific robot, but rather a system of commercially available off the shelf (COTS) components that can be easily integrated into DoD depot operations. This will allow individual depots to adapt the technology to meet their specific needs such as different component configurations or space limitations due to facility sizes.

Debugging of this system was performed at Concurrent Technologies Corporation (*CTC*) in Johnstown, Pennsylvania. Following debugging at *CTC*, a demonstration of this system was performed at the Oklahoma City Air Logistics Center (OC-ALC) at Tinker Air Force Base

(AFB), Oklahoma City, Oklahoma. The demonstration will validate the operation of the system on actual off-aircraft parts.

1.3 Regulatory Issues

Large quantities of hazardous waste are commonly generated by DoD depot-related activities. The wastes that are associated with coatings removal include the disposal of liquid paint removers and contaminated rinse water from chemical stripping operations and media waste from a variety of blasting processes. Chemical paint removers are the only process currently authorized for removing paint from KC-135 aircraft and components. In 2007, Tinker AFB reported using approximately 4,360 gallons of chemical paint removers and generated approximately 2.7 million gallons of contaminated rinse water from the stripping of KC-135 candidate components alone.

Coatings removal activities are impacted by a number of regulations promulgated under the Clean Water Act (CWA), Clean Air Act (CAA), and Resource Conservation and Recovery Act (RCRA). Washing surfaces following depainting operations can generate quantities of wastewater contaminated with methylene chloride or media and paint residue. Discharging wastewater with traces of hazardous waste can result in a direct violation of the CWA. The most common regulation associated with depainting activities is the CAA, including the recent efforts to minimize the use of HAPs such as methylene chloride. The RCRA directly regulates disposal of wastes generated by depainting activities. The RCRA regulates how and where depainting waste can be disposed and transported as well as any future liabilities resulting from environmental damage.

Chemical and mechanical coatings removal operations also require consideration for worker protection and training under the Occupational Safety and Health Act (OSHA), Air Force Occupational Safety and Health (AFOSH) standard, or other service specific occupational safety and health directives as appropriate. In the event where these standards overlap the more stringent standard is to be followed.

1.4 Stakeholder/End-User Issues

All branches of the DoD are currently involved in coatings removal operations and are concerned with the identification of alternative methodologies. Specifically, the elimination or reduction of the chemical paint strippers methylene chloride and phenol, dry media blasting using either plastic media or wheat starch, and hand sanding is of primary interest. The use of laser paint stripping systems is applicable to depainting activities on large off-aircraft components and weapons systems for the Air Force, Army, Navy, Marine Corps, and National Aeronautics and Space Administration (NASA).

This project built on previous SERDP projects PP-139 “Laser Cleaning and Coatings Removal” and PP-134 “Large Area Robotic Paint Stripping (LARPS)” which were undertaken to automate the coatings removal process. Available documentation for these projects was reviewed and personnel involved in the projects were interviewed to gain an understanding of the technical difficulties encountered and to gather lessons learned in order to develop a sound technical approach to help ensure successful completion of this project. Process engineers from OC-ALC

who worked on the LARPS system have been directly involved in every step of the development of the RLCRS system design. The primary obstacle identified with the LARPS system was the path programming to guide the water strip head across the aircraft surface. To help overcome this and other related technical challenges a team of industry leaders in robotic motion controls and systems integration, laser optics, beam delivery systems, lasers and laser depainting were assembled to assist with development of the RLCRS system.

2.0 TECHNOLOGY DESCRIPTION

2.1 Technology Development and Application

The RLCRS is made of several subsystems that are integrated together into an automated system. The individual components include the laser, robotic base, beam delivery system, laser scanner, and waste extraction systems. Each of these components is described in further detail in the following sections.

2.1.1 Laser

LASER, which is an acronym, stands for Light Amplification by Stimulated Emission of Radiation. A laser beam is generated by an energy source that excites atoms of a lasing medium to emit photons in an optical resonator. The energy source is typically an electrical discharge, flash lamp, or diode laser. The lasing medium may be a gas, such as carbon dioxide (CO_2) mixed with nitrogen (N_2) and Helium (He); a solid, such as Neodymium:Yttrium-Aluminum Garnet (Nd:YAG); or, although not common, a liquid. Stimulated emission occurs as two reflectors in the optical cavity mirror the emitted photons, further exciting other atoms to emit photons with the same wavelength, phase, and direction. The coherent radiation (laser beam) is then discharged through one of the reflectors (Figure 2-1).

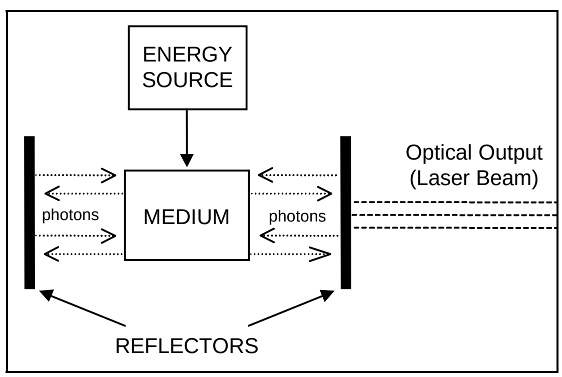

Figure 2-1: Light Amplification by Stimulated Emission of Radiation (LASER)

Optical output from a laser may be a continuous wave or pulsed beam, depending on how the reflectors are controlled. Continuous wave lasers reflect photons so that the number of stimulated emissions equals the number of photons in the optical output. These lasers are efficient in converting electrical energy to coherent radiation and, thus, have widespread industrial use.

The wavelength of light that is emitted by a laser is determined by the type of medium used to generate the beam. There are five main categories of lasers in use: solid-state, gas, excimer, dye, and semiconductor.

- Solid-state lasers have lasing material distributed in a solid matrix such as ruby or Nd:YAG lasers. The Nd:YAG laser emits infrared light at 1,064 nanometers (nm). The laser beams of Nd:YAG lasers can be delivered via fiber optical cable.

- Gas lasers commonly use helium, helium-neon, Argon, and CO_2 as the lasing medium and have a visible output of visible red light. CO_2 lasers emit energy in the far-infrared spectrum (10,600 nm), and have been used frequently in the metal fabrication industry for cutting hard materials. CO_2 laser can be pulsed using a transverse excitation at atmospheric pressure (TEA) method.

- Excimer lasers use reactive gases, such as chlorine and fluorine, mixed with inert gases such as argon, krypton or xenon. When electrically stimulated, a pseudo molecule (dimer) is produced. When lased, the dimer produces light in the ultraviolet range.

- Dye lasers use complex organic dyes, such as rhodamine 6G, in liquid solution or suspension as lasing media. They are tunable over a broad range of wavelengths.

- Semiconductor lasers are commonly called diode lasers and are not solid-state lasers. These lasers are usually very compact and very efficient. Diode lasers have been used in larger arrays such as laser printers or compact disc players. The diode lasers used for de-painting operations can be delivered via fiber optic cables at a wavelength of 808 or 940 nm.

In order to select an appropriate laser system that would meet the process requirements of large area coating removal an independent study was commissioned to determine the specifications required for any laser that would be implemented on the RLCRS. This study was performed by the Fraunhofer Institute and summarized in the report *Evaluation of Laser Gantry* (reference 1). The results of this study were evaluated and compiled into a performance based Request For Proposal (RFP) that was distributed throughout the laser industry. In response to this RFP, 15 different laser systems (nine CO_2, three Nd:YAG, and three diode laser systems) were proposed for use in the RLCRS by 10 different laser manufacturers. An intensive technical evaluation was performed of these commercial-off-the-shelf laser sources considering the laser specifications, maturity of the laser system, and maintenance requirements for the proposed laser system. At the completion of this evaluation a 6 kilowatt (kW) CO_2 laser from Rofin-Sinar was selected for use in the RLCRS. This laser provides the highest quality laser beam of any of the lasers that were proposed at a power level that is sufficient to rapidly remove coatings without causing excessive heating of the substrate. A picture of the Rofin-Sinar laser that was selected for use in the RLCRS is provided in Figure 2-2.

Photos courtesy of Rofin-Sinar

Figure 2-2: 6 kW CO_2 Laser System

2.1.2 Robotic Platform

The robotic base of the RLCRS system (Figure 2-3) is an existing gantry style robot that was designed and manufactured by PaR Systems, Inc., of Shoreview, Minnesota. This robot was originally manufactured in 1997 as part of a SERDP funded program and was available for this project at no cost. This gantry robot was selected for use in this project based not only on its availability, but also based upon several unique features of its design.

Figure 2-3: PaR XR125 Gantry Robot

First, this robot was a good candidate for use in this project due to its axis design. The PaR Robot was originally designed and used for a laser application; therefore, transport of the laser beam to the work-end of the robot was an integral part of the original robot design. To allow for the transport of the laser beam the gantry is equipped with hollow rotary joints at the rotational axis of the gantry. This allows for convenient placement of mirrors at these axis points.

The other consideration in the use of this robot was its size. The gantry robot's operating envelope (Table 2-1) was fairly consistent with the dimensions of the large off-aircraft parts that will be processed by the unit.

Table 2-1: Gantry Robot Work Envelope

Travel:	
X Bridge (2 motors)	9' 8"
Y Carriage (1 motor)	9' 8"
Z Mast (1 motor)	5' 0"
Rotation	
Θ^1 (1 motor)	370°
Θ^2 (1 motor)	210°
Θ^3 (1 motor)	370°

Because of the age of this equipment a full update of its control system was required. For this update all control hardware was replaced with a modern Giddings and Lewis motion controller and a new control software program was created.

A non-contact contour following system was also implemented as part of the revised control system. This contour following system allows for the robot to automatically process any part that fits within the operating envelope of the gantry. The system operates by using seven proximity sensors mounted at the work-head to develop a three dimensional map of the part surface. Any part that is placed in the operating envelope of the gantry robot will be processed using a series of slightly overlapping paths along the length of the part. The robot performs a mapping step as it moves from the front of the part to the rear; it then strips that area as it moves from the rear to the front. The next path over is mapped as the robot returns to the rear. The mapping and stripping pattern of a part is shown from the top view in Figure 2.4.

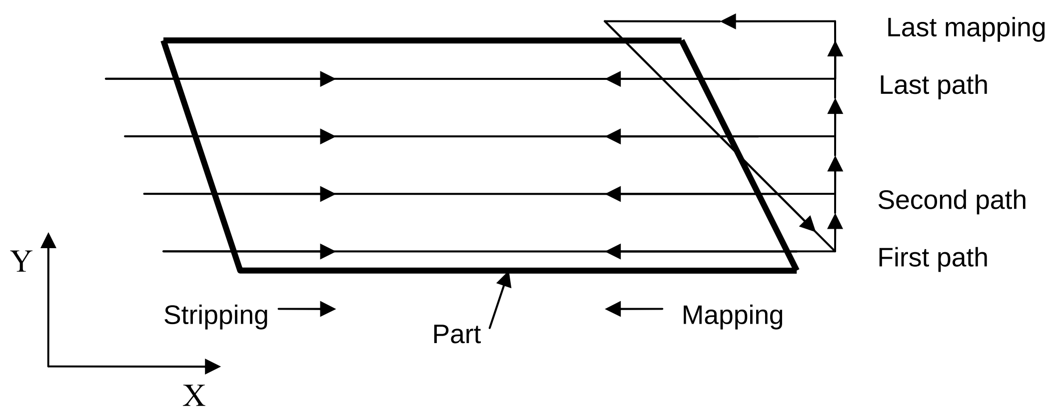

Figure 2-4: Contour Following Scheme

2.1.3 Beam Delivery System

The laser beam delivery system transfers the laser output to the work-end of the robot. Because high powered CO_2 lasers cannot be transferred via fiber optic cables the use of flying optics was required for the RLCRS system. The beam delivery system for the RLCRS is made up of a nine interlocked beam benders and two telescoping bellows tubes. An overview diagram of the beam delivery system is provided in Figure 2-5. The entire beam path from the laser source to the work-end of the robot is kept at a slight positive pressure to prevent the entry of dust or particulate into the beam path during robotic movements. This positive pressure is maintained by purging the beam path with highly purified air.

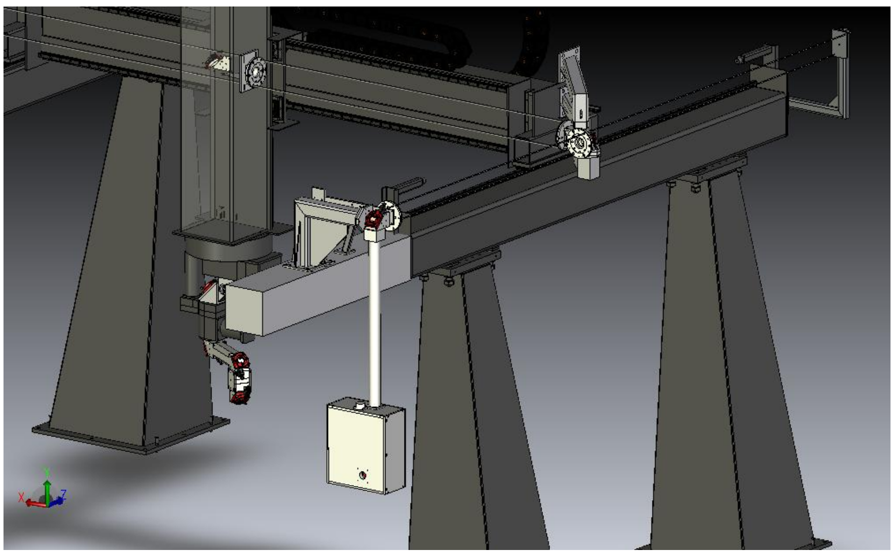

Figure 2-5: Beam Delivery System

2.1.4 Laser Scanner

A manipulation system controls the position of the laser as it moves over the substrate surface. The beam is directed to the target with the appropriate spot size and shape for delivering the energy density required for efficient coating removal. The spot is then rapidly rastered back and forth perpendicular to the direction of robotic movement.

For the RLCRS the powerSCAN 2D scanning system was selected. This is a commercially available system with numerous multi-kilowatt installations throughout the U.S, Europe and Asia. A reflective beam focusing module was designed for this application to accommodate the 6 kW power requirement and to produce a 0.7 millimeter (mm) x 7 mm elliptical spot. The elliptical spot geometry was selected to provide a more even overlap pattern as the beam is moved from side to side. The scanning system rasters the beam at a speed of 7 meters per second (m/s) with the acceleration/deceleration areas on either side of the scan being blocked by reflective copper beam blockers.

A picture of the RLCRS scanning system is provided in Figure 2-6.

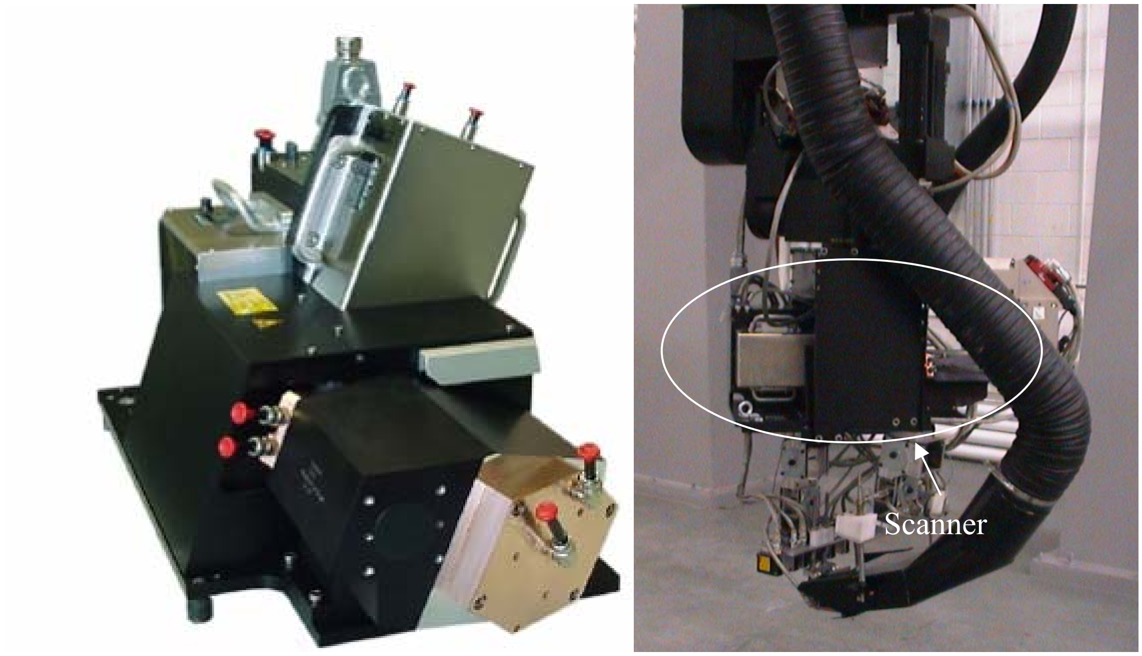

Photo courtesy of Scan Lab AG

Figure 2-6: Laser Scanning System

2.1.5 Waste Extraction System

As the coating is volatilized by the laser beam, decomposition by-products are thrown into the laser beam and incinerated to produce carbon dioxide, water, inorganic pigment ash, and trace amounts of other compounds. A transverse flow of air in the incineration zone is used to control combustion and collect effluents. The waste management system exhausts carbon dioxide, water, and trace gases into the atmosphere, and collects particulate matter in conventional filters for future disposal. Because of the incineration, the amount of waste to be disposed of represents only a fraction of the original coating volume.

For the RLCRS system, a waste collection nozzle was designed as shown in Figure 2-7. This nozzle includes an air knife to sweep the effluent out of the beam path and into an evacuation duct on the other side to collect the effluent. It is necessary to rapidly sweep all particulate and effluent from the beam path to avoid reduction in beam irradiance at the surface due to absorption by the effluent. A second air knife was mounted behind the stripping zone and directed to blow straight down at the part surface. This air knife provides secondary cooling to the part surface.

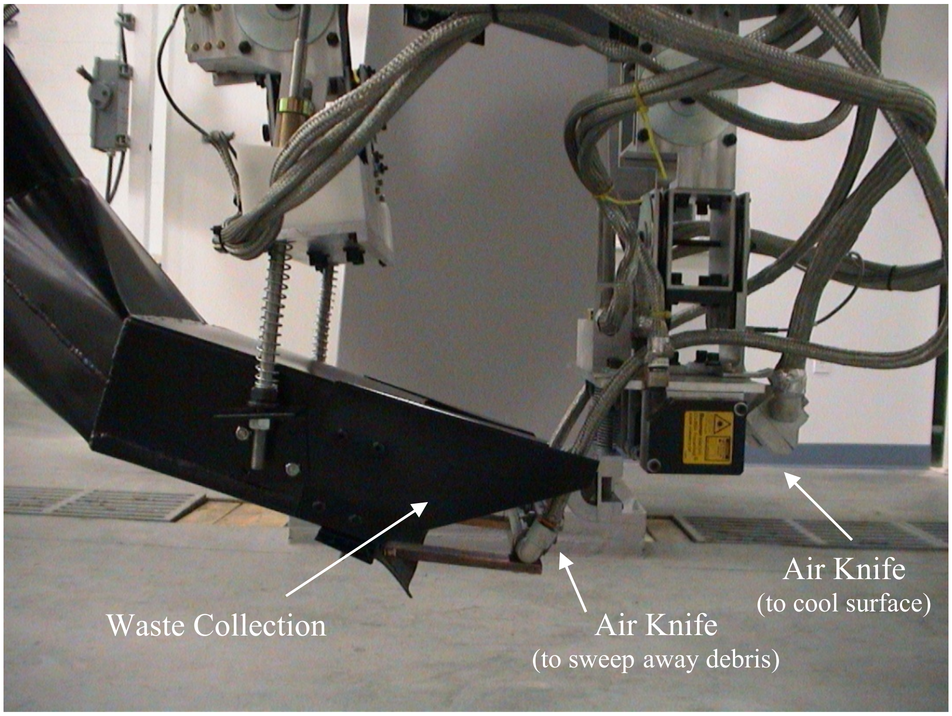

Figure 2-7: Waste Collection Nozzle

For the RLCRS effluent removal system, a 6-inch Exair "Standard Air Knife" operated at 100 pounds per square inch gauge (psig) with a 0.006-inch gap is used. The rated air velocity for this unit at 6-inches from the opening is 66 m/s. At this speed, the effluent plume will be swept more than the length of the beam ellipse in the time it takes for the beam ellipse to move its width at 7 m/s.

The air knife is designed to entrap air to minimize the air consumption. The amplification ratio is 30:1 at 6 inches from the nozzle, so the evacuation requirement for the evacuation system was approximately 2,200 standard cubic feet per minute (scfm) to keep up with the air flow and capture most of the effluent. For this purpose a TEKA Filtercube (Figure 2-8) was selected.

Figure 2-8: Evacuation System

Another key feature of the waste collection system is the collision detection protections. Because the air knife and vacuum shroud are kept very close to the surface during laser stripping (optimally 0.5 inch (in) above surface) accommodations were required to prevent part damage in the event that there is an error in the automated contour following. Both the air knife and vacuum shroud are mounted on a platform with spring loaded connections to prevent damage in the event of a crushing collision and with multi-axis breakaway joints to prevent damage in the event of a horizontal collision. All of these joints are equipped with proximity sensors that trigger a shutdown sequence in the control system in the event that one of these joints is activated.

2.2 Previous Testing of the Technology

2.2.1 Testing of Portable Handheld Lasers

The Portable Handheld Laser Small Area Supplemental Coating Removal System (PLCRS) project, through Environmental Security Technology Certification Program (ESTCP) Project WP-0027, demonstrated several portable handheld laser systems using test panels constructed of aluminum, steel, and composite materials. The objective of the demonstration was to verify the ability of candidate laser systems to effectively remove coatings that are commonly used throughout the DoD without causing physical damage to the substrate. The demonstration was performed from February 2001 through August 2005, in the Laser Hardened Materials Evaluation Laboratory (LHMEL) at Wright Patterson Air Force Base (WPAFB) in Dayton, Ohio. The testing included an evaluation of the effects of the laser on the material properties of aerospace substrates, as well as evaluations of the environmental safety and occupational health aspects of the systems themselves. These test results, documented in the project final report entitled *Portable Handheld Laser Small Area Supplemental Coatings Removal System Final Report* (reference 2), showed that the CO_2 and Nd:YAG laser systems that were evaluated do not significantly affect the substrate materials and are effective, versatile tools for coating

removal applications. As a portable coating removal laser system, the Nd:YAG laser was the most suitable COTS system.

2.2.2 Coating Removal on Aluminum Panels Using a CO_2 Laser System

The Materials Integrity Branch of the Air Force Research Laboratory (AFRL), located at WPAFB evaluated the laser stripping of two 2024-T3 aluminum-clad (Al-clad), chromate conversion-coated panels with two different coating systems. The laser system used was a 250 Watt (W), pulsed TEA-CO_2 laser. Microhardness test results indicated that the bulk alloy of both stripped panels was unaffected by the stripping process. Therefore, mechanical properties do not appear to have been degraded; however, mechanical testing is necessary to validate this conclusion (reference 3).

2.2.3 Coating Characteristics and Removal Efficiency

One property of the coating system that was thought to affect the ability of the laser technology to remove it was the age of the coating system. In personal communications with JET Lasersysteme GmbH and Selective Laser Coating Removal Lasertechnik GmbH, each company indicated that in their experience with aerospace coatings, no difference was observed in the laser removal of artificially aged and freshly cured paint. One property of the coating system that can impact the ability of the laser technology to remove the coating is the pigments that add color to the coating system.

Research conducted by Penn State University and documented in the report entitled, *An Investigation of Laser Based Coating Removal* (reference 4), indicates that the pigment in coating systems can significantly effect the performance of pulsed lasers due to the low peak irradiance and the pigment's ability to absorb it. However, the irradiance of the Q-switched pulsed laser is high enough that energy is absorbed into the coating regardless of color resulting in ablation of the coating.

2.3 Factors Affecting Cost and Performance

Several key factors affect the cost and performance of the RLCRS system. The first factor effecting cost is that the laser system strip rates must be equal to or faster than the coating removal rate of the process that is being replaced. Similar to current coating removal methods such as chemical stripping or media blasting, the strip rate of the laser system is expected to vary with coating characteristics such as thickness and chemical composition. Regardless of the coating removal method, thicker coating systems take longer to remove than thin coating systems and hard, dense coatings such as chemical agent resistant coatings are more difficult and take longer to remove than standard polyurethane coating systems. One factor that may affect the laser coating removal rates more than conventional methods is the initial surface gloss or reflectivity of the coating system. This should not present any major obstacle since the vast majority of the components expected to be depainted with the RLCRS are medium to dark flat gray and the energy density of the laser system should be sufficient to effectively remove the limited amounts of gloss paints expected to be encountered. Another factor that may influence strip rates is the possible requirement to decrease laser power to strip delicate substrates. This is analogous to reducing air pressure and using less aggressive media when blasting delicate

surfaces such as composites or thin skin honeycomb parts and, in both cases, the strip rates will decrease.

Secondly, it is important to ensure that the laser system is utilized close to 100% of its available time, this will allow for expedient recovery of the systems initial cost.

When these factors are met the RLCRS is financially viable as an alternative coating removal technology for large off-aircraft components.

2.4 Advantages and Limitations of the Technology

In the past decade, laser systems have generated significant interest as cleaning and paint removal tools. The advantages of using lasers for paint removal are that it requires no sample preparation, is non-contact, and uses no secondary medium that increases the amount of material to dispose.

A potential limitation to the technology is the potential for the energy beam to overheat the substrate while performing stripping operations. The controllable nature of the energy beam that is used in the system being evaluated in this task addresses this issue. With the proper parameters, coatings can be selectively removed with minimal influence to the underlying substrate.

In general, the robotic laser system is most suited for use on parts that have the following characteristics:

- Metallic, composite, or fiberglass substrate – preferably (but not necessarily).
- Simple part geometry – gradual contours are preferred over sharp angles for speed of manipulation.
- Organic coating system to be partially or completely removed – selective coating removal is possible but will not be evaluated for the RLCRS.
- Relatively continuous process throughput – a laser system performs better if used regularly, rather than intermittently.

3.0 DEMONSTRATION DESIGN

3.1 Performance Objectives

The main performance objective of this demonstration was to remove coatings from large off-aircraft parts using the robotic laser coating removal system without causing damage to the substrate materials. The performance objectives for this demonstration are detailed in Table 3-1.

Table 3-1: Performance Objectives

Type of Performance Objective	Primary Performance Criteria	Expected Performance Metric	Actual Performance (Objective Met?)
Quantitative	Maintain specifications for affected parts/ substrates	Pass individual material tests described in the Joint Test Protocol (JTP)	Yes
Qualitative	Coating removal without substrate damage	No visual damage	Yes
Quantitative	Meet or exceed current coating removal process rates	Meet or exceed current coating removal process rates which include prep time, strip time, and clean-up time	Yes

3.2 Selecting Test Platform/Facilities

This demonstration was conducted at OC-ALC, which will serve as the final installation point for this system. Demonstration of the system was performed using large off-aircraft components of the KC-135. These components were selected due to the high volume of parts that are processed, the sizes of the parts, and the willingness of the KC-135 program to participate.

3.3 Test Platform/Facility History/Characteristics

OC-ALC's mission is dedicated to providing worldwide technical logistic support to Air Force aerospace weapon systems, as well as associated equipment and commodity items. Its major product line directorates of aircraft, propulsion and commodities manage, maintain and procure resources to support first-line overhaul and maintenance of B-1, B-2 and B-52 bombers, the E-3, the multipurpose KC-135 aircraft, and several missile systems. The center's facilities house some of the most sophisticated technical repair and manufacturing processes in the world, acquiring and maintaining aviation systems in partnership with customers and suppliers. Other directorates furnish center-wide services such as environmental management, financial management, procurement policy, technical and industrial plant maintenance and computer services.

The OC-ALC encompasses 138 acres of indoor maintenance facilities and 93 acres of covered warehouse space. Historic Building 3001, headquarters of the OC-ALC, covers 62 acres and stretches for seven-tenths of a mile. Within its walls, workers perform a vast array of maintenance on aircraft, engines, components and accessories and perform a multitude of necessary administrative tasks.

3.4 Present Operations

The RLCRS system is intended to replace the current chemical stripping process that is performed for large off-aircraft components of the KC-135. The identified components include the elevators, main landing gear doors, flaps, rudders, and ailerons. The chemical stripping of the candidate KC-135 components was targeted as the initial process for implementation of the RLCRS system, but the system can potentially be utilized on all types of large off-aircraft components from all different types of aircraft throughout the depots.

The current depainting process of large off-aircraft parts consists of six major process steps as shown in Figure 3-1. The parts are first washed with an alkaline wash to remove dirt and grease. After specific areas of the parts are masked-off, chemical stripper is spray applied and allowed to soak for a period of time. The parts are then rinsed with water to remove the loose paint. Any residual paint is removed with additional applications of chemical stripper. The parts then receive a final rinse and the masking materials are removed.

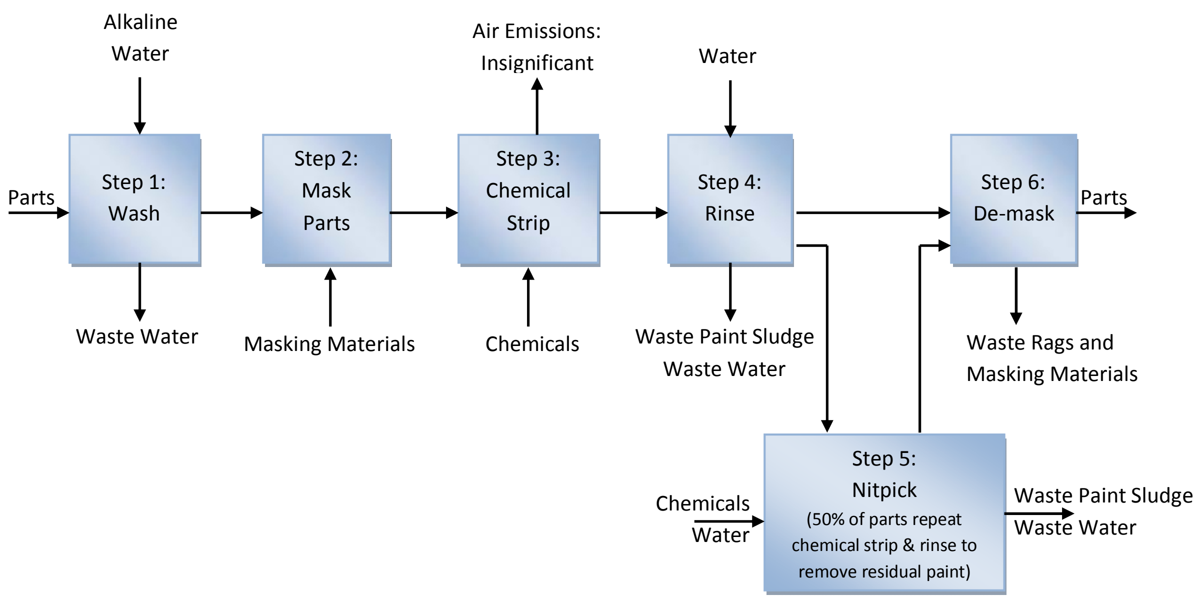

Figure 3-1: Chemical Depainting Process for Large Off-Aircraft Parts

The chemical process is a relatively long process that requires long dwell times for the chemicals to work. Because these chemicals are sprayed on and allowed to dwell for a specified period of time the overall processing time is relatively independent of the part size. Typically after the bulk chemical stripping several additional applications to specific areas are required to “Nitpick” areas that were not stripped during the bulk stripping. Overall the chemical stripping process can take up to 2 full flow days to process the parts that are targeted for the RLCRS system.

3.5 Pre-Demonstration Testing and Analysis

Prior to the demonstration at OC-ALC, debugging and optimization testing of the RLCRS was conducted at *CTC*. Diagnostic tests of the functionality of the RLCRS were performed to measure the laser beam delivery system stability, beam losses, beam power and spot size at the

work surface, scan speed provided by the scanner, contour follower fidelity, and effluent control air flow rate. Optimization testing was conducted to determine the operating parameters that were used throughout the demonstration. This testing was devoted to optimizing the air flow geometry, laser beam parameters, and scan parameters to achieve good coating removal rates with minimal substrate heating. This testing was described in detail in the *Draft Test Plan for RLCRS Operational Readiness and Process Optimization Tests* (reference 5). Specifically, the testing evaluated:

- Laser power (held constant at maximum value for most tests)
- Irradiance spot size (varied by varying the scanner working distance)
- Scan width (held constant at 100 mm for most tests)
- Scan rate (held constant at highest possible rate)
- Laser beam duty cycle (held constant for most tests)
- Robot mast sweep speed
- Robot mast sweep direction relative to air flow direction
- Number of robot arm sweep passes
- Air knife pressure

Screening testing was performed during the debugging/optimization testing at *CTC* in order to demonstrate that the use of the RLCRS causes no effect on the part substrate beyond the effects currently encountered using chemical stripping. All panel testing was performed in accordance with the approved JTP (reference 6). This JTP detailed the tests that were performed, the frequency of these tests and the standard procedures that were followed for each of the tests. This debugging/optimization testing was also described in further detail in the *ESTCP Demonstration Plan for Debugging/Optimization* (reference 7).

This testing was conducted using 24 inch x 18 inch test panels constructed of the various substrates and coating systems that are representative of the parts that were processed using the RLCRS. Each of these test panels was subjected to four coating and laser stripping cycles. The mechanical test results from the laser stripping of these test panels was compared to the baseline unprocessed "control" panels, to unprocessed panels that had been subjected to the baking step that is part of the artificial aging process, and to test panels that had been stripped using the conventional chemical depainting processes.

An overview of the results of the screening testing that was conducted is presented in Table 3-2. A description of each of the test procedures that were followed, the testing methodologies, and a discussion of the results of each test is provided in the Joint Test Report (JTR), Appendix A.

Table 3-2: Data Summary

Performance Criteria	Baseline	Baseline Baked	Laser Stripped	Chemically Stripped	Acceptance Criteria
Coating Strip Rate (ft²/min)					
2024 Al – Bare	n/a	n/a	1.0	n/a	Information purposes only
2024 Al - Clad	n/a	n/a	1.0	n/a	
2024 Al – Anodized	n/a	n/a	0.8	n/a	
7075 Al – Bare	n/a	n/a	1.0	n/a	
Aluminum Honeycomb 0.010" Face Sheet	n/a	n/a	0.9	n/a	
Aluminum Honeycomb 0.016" Face Sheet	n/a	n/a	0.9	n/a	
Visual Damage Assessment					
2024 Al – Bare	No surface abnormalities	No surface abnormalities	No surface abnormalities	No surface abnormalities	No visual warping, burning, thermal effects or other damage at 10X magnification
2024 Al - Clad	No surface abnormalities	n/a	No surface abnormalities	n/a	
2024 Al – Anodized	No surface abnormalities	n/a	Warping, burning of anodize layer	n/a	
7075 Al – Bare	No surface abnormalities	No surface abnormalities	No surface abnormalities	No surface abnormalities	
Aluminum Honeycomb 0.010" Face Sheet	No surface abnormalities	No surface abnormalities	No surface abnormalities	No surface abnormalities	
Aluminum Honeycomb 0.016" Face Sheet	No surface abnormalities	No surface abnormalities	No surface abnormalities	No surface abnormalities	
Substrate Temperature (°F)					
2024 Al – Bare	n/a	n/a	271° F	n/a	300° F max for aluminum 180° F max for honeycomb
2024 Al - Clad	n/a	n/a	287° F	n/a	
2024 Al – Anodized	n/a	n/a	248° F	n/a	
7075 Al – Bare	n/a	n/a	261° F	n/a	
Aluminum Honeycomb 0.010" Face Sheet	n/a	n/a	161° F	n/a	
Aluminum Honeycomb 0.016" Face Sheet	n/a	n/a	160° F	n/a	
Superficial Hardness (HR15T)					
2024 Al – Bare	83.0	83.4	82.9	82.8	Compare with baseline sample
7075 Al - Bare	88.4	88.8	88.7	89.0	
Electrical Conductivity (%IACS)					
2024 Al – Bare	30.2	30.1	30.1	30.0	Compare with baseline sample
7075 Al - Bare	32.0	32.2	32.1	32.2	

Table 3-2: Data Summary (continued)

Performance Criteria	Baseline	Baseline Baked	Laser Stripped	Chemically Stripped	Acceptance Criteria
Tensile Properties					
Yield Strength (ksi)					Compare with baseline sample
2024 Al – Bare	53.1	52.7	52.7	52.5	
7075 Al - Bare	75.0	75.7	76.0	75.6	
Tensile Strength (ksi)					
2024 Al – Bare	71.4	71.5	71.6	71.3	
7075 Al - Bare	84.7	85.0	84.9	85.0	
Elongation (%)					
2024 Al – Bare	16.4	17.0	16.9	17.1	
7075 Al - Bare	13.7	12.7	12.9	13.2	
Fatigue Properties					
Average Cyclic Life (cycles) – Max Stress 45 ksi					Compare with baseline sample
2024 Al – Bare	312,743	192,281	166,619	184,578	
7075 Al - Bare	93,904	118,372	133,809	64,732	
Average Cyclic Life (cycles) – Max Stress 55 ksi					
2024 Al – Bare	40,562	52,628	40,305	57,941	
7075 Al - Bare	36,764	22,776	32,421	31,320	
Ultrasonic Inspection					
Aluminum Honeycomb 0.010” Face Sheet	No discontinuity	No discontinuity	No discontinuity	No discontinuity	No discontinuity
Aluminum Honeycomb 0.016” Face Sheet	No discontinuity	No discontinuity	No discontinuity	No discontinuity	
Peel Resistance (Average Peel Torque (in-lb$_f$/in))*					
Aluminum Honeycomb 0.010” Face Sheet	23.5	22.8	23.2	25.6	Compare with baseline sample
Aluminum Honeycomb 0.016” Face Sheet	27.9	19.9	27.2	26.1	
Flexural Testing (Average Peak Flexural Load (lb$_f$))*					
Aluminum Honeycomb 0.010” Face Sheet	950	1172	1267	986	Compare with baseline sample
Aluminum Honeycomb 0.016” Face Sheet	1447	1557	1202	1436	

*AFRL/RXSA determined that the panels as manufactured are not representative of structural materials used on flight controls; therefore, no valid conclusions can be drawn from this data set. Peel resistance testing will be redone using new honeycomb structural materials.

Screening test results indicated that use of the RLCRS has no detrimental effect on 2024 and 7075 aluminum substrates. All testing that was performed on these substrates including superficial hardness, conductivity, tensile testing, and fatigue life showed no degradation in material properties from baseline conditions.

The screening test results show that use of the RLCRS on honeycomb structures causes no detectible defects when visually examined and subjected to ultrasonic inspection. Additionally, the testing showed that the backside of the honeycomb face sheet will not be exposed to temperatures greater than 161°F during processing when the RLCRS is operated at a robotic sweep speed of 3.75 inchs/second. Due to inadequacies in the manufacturing of the honeycomb structural test materials comparisons in the effects of the RLCRS on peel resistance and flexural properties cannot be made. It is recommended that additional honeycomb structural test materials be procured and this testing be repeated.

3.6 Testing and Evaluation Plan

3.6.1 Demonstration Set-Up and Start-Up

The RLCRS system was transitioned to and installed at OC-ALC for the full ESTCP demonstration. A photo of the RLCRS system as it was installed is shown in Figure 3-2. Initially, the RLCRS was to be housed in the OC-ALC depaint facility in Building 2122. However, because of space availability and timing concerns, the system was installed in Building 3105. This facility provided some advantages in that there was an existing enclosure present in the building that was suitable to house the RLCRS. This enclosure had the required utilities present and was suitably sized to house the RLCRS and to allow for staging of the large off-aircraft components. Additionally, this enclosure was equipped with an overhead gantry crane that is suitable for lifting of the off-aircraft parts from their trailers and positioning them onto the RLCRS part cart. A diagram of the building and the layout for the equipment once it is installed is shown in Figure 3-3.

Figure 3-2: RLCRS Installed at OC-ALC

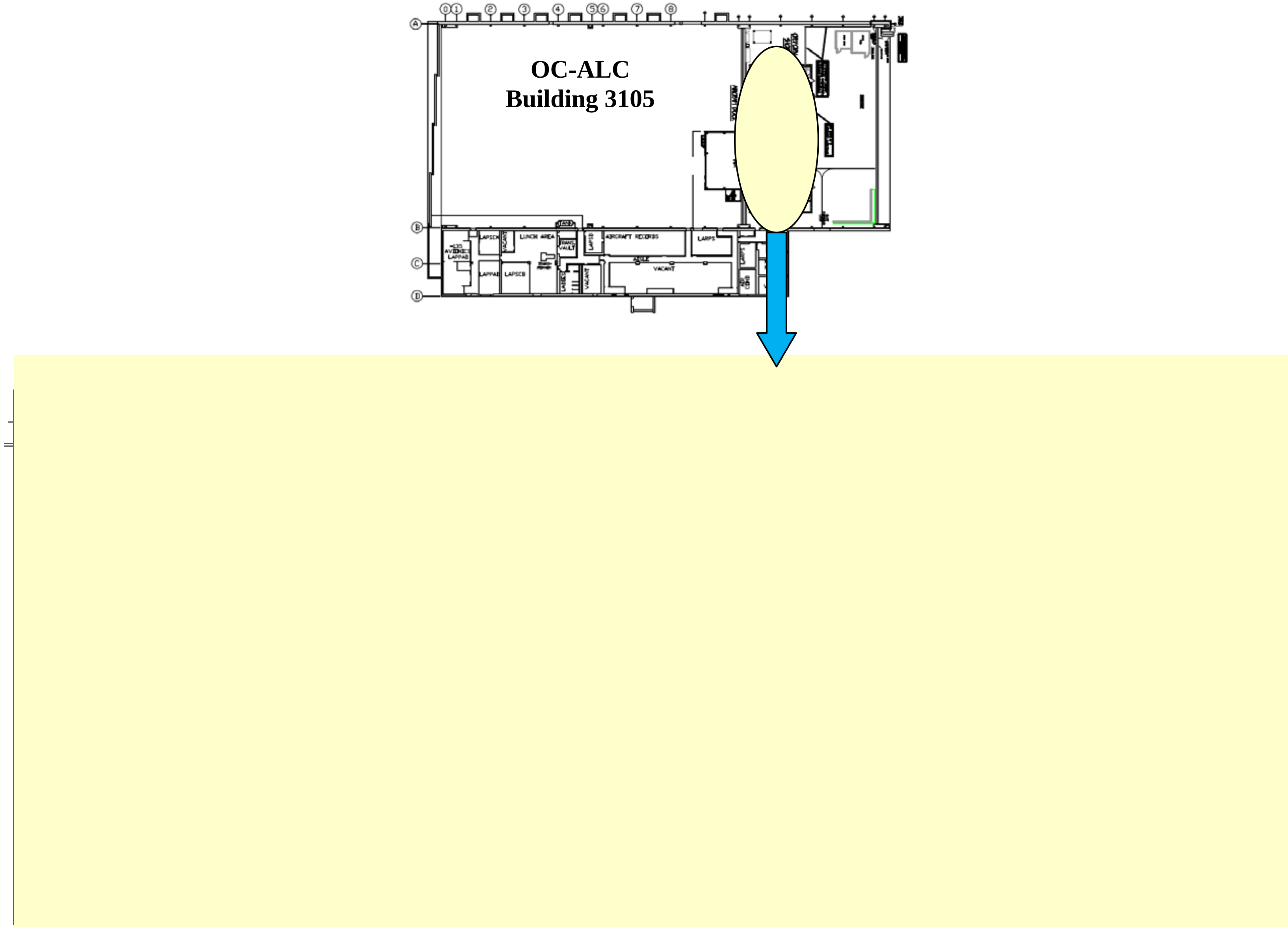

Figure 3-3: OC-ALC Facility Layout for Installation of RLCRS

3.6.1.1 Health and Safety Requirements

The laser used in the RLCRS is a Class 4 laser, and requires specific safety requirements as outlined in AFOSH Standard 48-139, American National Standards Institute (ANSI) Z136.1-2007 and the OSHA) instruction standard PUB8-1.7.

Personnel who routinely work in the laser environment are required to undergo a medical examination. Medical examinations are required before an individual's initial assignment to laser duties and as soon as practical following termination of duties involving lasers. Periodic examinations are not required under the relevant standards. Medical examinations will involve:

- Ocular history: past ocular history and family history
- Visual acuity: best corrected, distant and near vision measured
- Macular function: macular function tested with an Amsler grid
- Color vision: color vision test to document color vision discrimination

Additionally, for Class 4 Lasers there are several factors that are required to be calculated to determine the Hazard Areas. Maximum Permissible Exposure (MPE) is the value of energy deposition below which no adverse biological effect is expected. Nominal Ocular Hazard Distance (NOHD) is the distance from the output aperture in which irradiance is not expected to exceed the appropriate MPE for unobstructed viewing by the human eye. Nominal Hazard Zone (NHZ) is the space in which laser radiation exceed the applicable MPE. Any personnel who work within the NHZ must be provided with PPE and training in its use. The US Air Force (USAF) has an approved laser hazard analysis software package, LHAZ 4.0 Pro, for calculating these values. Table 3-3 provides the relevant data from the LHAZ report that was generated for the RLCRS system.

Table 3-3: LHAZ Hazard Analysis

Parameter	Value
Wavelength	10.6 micrometers (μm)
Output Mode	Continuous Wave
Average Power	6 kW
Beam Profile	Elliptical
Beam Distribution	Gaussian
Beam Divergence	0.15 x 0.15 milliradian (mrad)
Beam Diameter	0.7 x 4.5 mm
Exposure Duration	10 seconds (s)
Exposure Range	10 centimeters (cm)
Laser Classification	Class 4
MPE (Ocular)	$1.00e^{-001}$ watts per square centimeter (W/cm^2)
MPE (Skin)	$9.958e^{-002}$ W/cm^2
NOHD (Ocular)	59,962.5 feet (ft)
NOHD (Skin)	60,086.6 ft
NHZ (Ocular)	4.52 ft
NHZ (Skin)	1.43 ft
Maximum Optical Density	5.79

In accordance with the AFOSH and ANSI standards, wherever possible, engineering controls have been instituted to ensure a safe environment for the system operators. Foremost was the construction of a separate control booth that encloses the operator. The operator is not able to fire the laser beam unless he is operating the system from inside the control room. Additionally, appropriate interlocks are in place to shut down the laser if the door to the enclosure is opened during operation. The window of this enclosure is constructed of an acrylic material of suitable thickness to provide the required optical density (OD) for viewing the laser coating removal process.

Also, appropriate engineering controls were instituted into the RLCRS system itself. In accordance with ANSI Z136.1-2007 these controls include, but are not limited to:

- Interlocked protective housing for the laser source that prevents any light from leaking out
- Key control of laser source
- Beam Stop that prevents the beam from leaving the source without having to shut down the laser.
- Fully enclosed beam path with interlocks on each mirror in the system
- Activation warning system that includes an audible siren and a visible light
- Laser emission delay
- Emergency stop or “Panic Buttons” located at various points in the laser enclosure and in the operators booth
- Interlocked doors to the enclosure and to the operator control booth

3.6.2 Period of Operation

Prior to this demonstration, the system underwent nine months of debugging and evaluation at *CTC* in Johnstown, Pennsylvania. Following completion of the debugging, the system was disassembled and transported to OC-ALC in October through November 2007. The system start-up was performed in December 2007 and the full ESTCP demonstration was performed on off-aircraft parts in March through April 2008.

3.6.3 Amount/Treatment Rate of Material to be Treated

The demonstration at OC-ALC consisted of product testing of the ability of the system to effectively strip KC-135 flight control components that undergo depainting during the course of routine depot maintenance operations. One of each of the following parts were processed:

- KC-135 Aileron, outboard
- KC-135 Elevator
- KC-135 Landing gear door
- KC-135 Rudder
- KC-135 Wing flap, outboard

3.6.4 Operating Parameters for the Technology

The operating parameters that were used during processing of parts for the demonstration were established during the debugging/optimization testing at *CTC*. The key operating parameters that were established and followed throughout the demonstration are detailed in Table 3-4. These settings were selected to provide the maximum coating removal rate without causing damage to the part substrate.

Table 3-4: Operating Parameters

Operating Parameter	Unit of Measure
Laser Power	6000 W
Laser Power at surface	4500 W
Focused Spot Size	0.7 mm x 4.5 mm ellipse
Irradiance	102.3 kW/cm^2
Scan Rate	7 m/s
Scan Width	127 mm
Stand-Off Distance	500 mm
Sweep Rate – bare, clad substrates	1.75 inch per second (in/s)
Sweep Rate – anodized substrates	3.0 in/s
Sweep Rate – Honeycomb - 0.010 inch face sheet	3.0 in/s
Sweep Rate – Honeycomb - 0.016 inch	2.5 in/s
Sweep Rate – Honeycomb - alternate setting for both face sheet sizes	3.75 in/s

3.6.5 Experimental Design

Demonstration testing was conducted on large off-aircraft parts in accordance with Section 4.0 of the JTP.

All aircraft parts that were processed during this demonstration were subjected to a visual examination for any existing damage prior to being stripped by the RLCRS. Any existing damage was documented. The parts were then subjected to a visual examination following laser depainting operations and any damage or surface changes were documented.

The average coating thickness of every part was measured and recorded prior to processing. This measurement was performed using a Positector Model 6000-3 eddy current coating thickness gage. Twelve (12) measurements were taken for each part and used to calculate an average coating thickness.

The surface area of every part was calculated to allow for a determination of the percentage of surface area of the part that was processed using the RLCRS. Each part was measured, and a

dimensional diagram of the part was produced. This drawing was then imported into a solid modeling program in order to accurately calculate the total surface area of the part.

Every part was then stripped using a consistent set of parameters. The JTP called for substrate temperature to be recorded during demonstration testing, but it was discovered that this was not feasible without modifying the various aircraft parts due to their shape and construction. Because extensive temperature monitoring was performed during the screening testing, it was decided to omit the temperature evaluation on the actual parts.

3.6.6 Product Testing

The test results from the laser stripping of these parts is provided in the JTR found in Appendix A. An overview of the demonstration tests that were conducted is presented in Table 3-5. A description of each of the test procedures and a discussion of the test results are provided in the following sections.

Table 3-5: Demonstration Testing Overview

Performance Criteria	Laser Strip				
	Landing Gear Door	**Rudder**	**Outboard Flap**	**Elevator**	**Outboard Aileron**
Coating Strip Rate (ft^2/min)	1.53 (~2.6 mils)	1.12 (~6.1 mils)	1.86 (~3.4 mils)	1.86 (~3.6 mils)	2.03 (~3.4 mils)
Coating Strip Rate per mil coating removed (ft^2*mil/min)	3.97	6.81	6.33	6.79	7.41
Visual (Warping/Denting)	No	No/Yes*	No	No	No

* The rudder had one section of the part that was a magnesium substrate. This substrate was not one of the substrates that had been identified for this project; therefore, no optimized laser parameters had been developed for safe processing on magnesium. As a result, the magnesium panel did incur warping. Because there is currently no laser operating parameters for magnesium substrates that will not damage the substrate, a procedure for operators to check for the presence of magnesium prior to processing a part has been established.

All parts that were processed during this demonstration were moved, positioned, and processed by OC-ALC who had been previously trained on the operation of the RLCRS. *CTC* personnel attended this demonstration, provided guidance as to the most advantageous processing scheme for each part, and recorded all processing data.

3.6.6.1 KC-135 Landing Gear Door

The first production part that was selected for this demonstration was the KC-135 Landing Gear Door. For the purposes of this demonstration, a condemned Landing Gear Door was obtained. The two outside surfaces of the door were selected as candidate surfaces for processing using the RLCRS system. These two part surfaces were previously processed by OC-ALC using the automated high pressure water system that was recently disapproved by the KC-135 Program Office. Only the two outside surfaces were stripped using the water jet system due to the

complex geometry that exists on the interior surfaces. Interior surfaces were depainted using chemical stripping agents.

Pictures of the landing gear door prior to laser treatment are provided in Figure 3-4. The coating that was on this part was measured to be between 2.2 to 3.2 mils thick (average thickness measured was 2.6 mils). Because this was an old, condemned part, the coating formulation was unknown, but it was observed to be a gray coating that was severely aged and weathered. Additionally, this part was heavily covered with dirt and grease.

Figure 3-4: Landing Gear Door Prior To Laser Stripping

Due to the limitations of the RLCRS operating envelope, the landing gear door was processed by first stripping Surface One, and, then, opening the door and laying Surface Two flat on the parts cart. No masking was required for this part, and no cleaning or removal of surface contaminants was performed prior to laser processing. Surfaces One and Two were completely stripped by the RLCRS. No attempt was made to process the two inner surfaces.

This part took 5 minutes to initially position on the parts cart and prepare for stripping. Surface One was stripped in 39 minutes. The part was then repositioned for processing of Surface Two. This repositioning took 6 minutes. Surface Two was then stripped in 49 minutes. All of these actions totaled 99 minutes to completely process the outside surfaces of this part. Pictures of the stripped surfaces are provided in Figure 3-5.

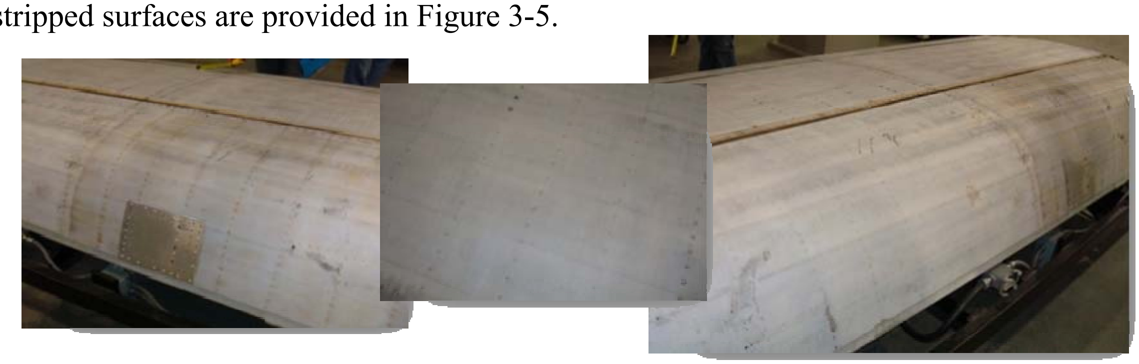

Figure 3-5: KC-135 Landing Gear Door after Processing Using the RLCRS

The stripped surfaces of the part were completely free from coating and showed no visual indications of damage. The two surfaces that were stripped during this demonstration were in a suitable condition to be sent for repainting after washing. The calculated results of this testing, including coating removal rate, fluence, and strippable area assessment, are detailed in Table 3-6.

Table 3-6: Results for Assessment of KC-135 Landing Gear Door

Parameter	Value
Coating Thickness	2.6 mils
Number of Stripping Passes	3
Total Process Time (including set-up/masking/etc.)	99 minutes
Surface Area Stripped	56.89 ft^2
Total Fluence	152.18 Joules per square centimeter (J/cm^2)
Coating Removal Rate	1.53 ft^2/min
Coating Removal Rate Per mil Coating Removed	3.97 square feet per minute per mil removed (ft^2-mil/min)
Total Part Processing Rate	0.57 ft^2/min
Strippable Area	100% of selected surface area 45% of total surface area

3.6.6.2 KC-135 Rudder

A condemned KC-135 rudder was obtained and used for the second part demonstration. Pictures of the part prior to laser treatment are provided in Figure 3-6. The coating that was present on this part was measured to be 4.5 to 8.2 mils thick (average of measurements is 6.1 mils). The paint system present on this part was not identified, but it consisted of a severely aged white topcoat and a green primer. Also present on the part surface were black and yellow striping as well as, several instances of lettering.

Figure 3-6: KC-135 Rudder Prior to Laser Stripping

Due to the large size and weight of this part, initial placement of it on the parts cart took slightly longer than the other parts. In total, 15 minutes were spent moving the part from its trailer to the cart and masking three small areas on the surface. This part was able to be processed by the RLCRS system by staging each side through 3 positions along its length. Movement of the part to each of these sections was accomplished using the RLCRS's semi-automated parts cart.

It took six passes and 180 minutes to strip the coating from each side of the rudder. In total, 390 minutes were spent preparing and processing this part. The coating on this part was difficult to remove and atypical for what is usually processed at OC-ALC. When a typical coating is encountered, this time is expected to be reduced. Pictures of the stripped surfaces are provided in Figure 3-7.

Figure 3-7: KC-135 Rudder After Processing Using the RLCRS

A small amount of primer was left in the areas where the striping and lettering was present. A decision was made to leave these small areas to be stripped using the handheld lasers as part of touch-up operations instead of performing a sixth pass over the entire surface.

During stripping of the rudder it became apparent that one section of the part was made of a different substrate than aluminum. After stripping was completed, it was revealed that this section was a magnesium substrate. Conversations with the operators and OC-ALC personnel revealed that this substrate is found occasionally on the different parts that are processed. This substrate is not one of the substrates that had been identified for this project, so no optimized laser parameters had been developed for safe processing on magnesium. A picture of the substrate after processing using the current parameters is provided in Figure 3-8.

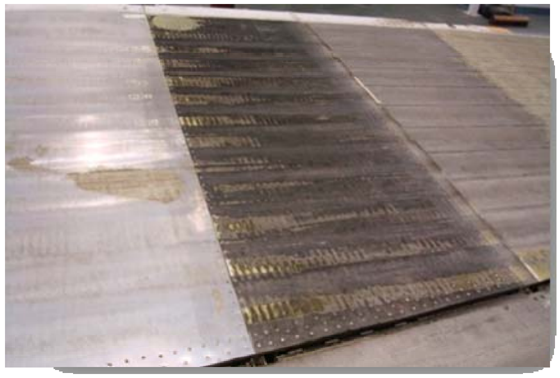

Figure 3-8: Detail of Damage to Magnesium Substrate

Because it is not known if this substrate will be encountered prior to processing, a method for determining its presence is needed. AFRL Non-Destructive Inspection (NDI) personnel have advised the project team that detection of magnesium can be accomplished using an eddy current conductivity meter. Because there are currently no laser operating parameters for magnesium substrates that will not damage the substrate, it is recommended that RLCRS operators take conductivity measurements of the main sections of the parts prior to processing. Sections that are found to have a magnesium substrate can be masked or the entire part can be routed to traditional chemical stripping areas. Details of the full set of calculated results for the demonstration of the KC-135 rudder are provided in Table 3-7.

Table 3-7: Results for Assessment of KC-135 Rudder

Parameter	Value
Coating Thickness	6.1 mils
Number of Stripping Passes	5
Total Process Time (including set-up/masking/etc.)	390 minutes
Surface Area Stripped	201.60 ft^2
Total Fluence	253.64 J/cm^2
Coating Removal Rate	1.12 ft^2/min
Coating Removal Rate Per mil Coating Removed	6.81 ft^2-mil/min
Total Part Processing Rate	0.52 ft^2/min
Strippable Area	82% of total surface area

3.6.6.3 KC-135 Elevator

The next part that was processed was a condemned KC-135 elevator. Pictures of the part prior to laser treatment are provided in Figure 3-9. The coating on this part was measured to be 2.5 to 5.4 mils thick (average of measurements is 3.65 mils). The paint system was the standard MIL-

PRF-23377 primer and MIL-PRF-85285 topcoat that is normally applied to these parts at OC-ALC. This part had been recently painted by OC-ALC.

Figure 3-9: Elevator Prior To Laser Stripping

Use of the overhead crane was required to move the elevator from its storage trailer and position it on the parts cart. In total, 10 minutes were spent preparing this part for processing. This part was able to be processed by the RLCRS system by staging each side through 3 positions along its length. Movement of the part to each of these sections was accomplished using the semi-automated parts cart.

Laser stripping of the KC-135 elevator took 3 passes for each section and totaled 79 minutes for each side. When the positioning and masking steps are included, the part took a total of 173 minutes to process. Pictures of the stripped surfaces are provided in Figure 3-10.

Figure 3-10: KC-135 Elevator After Processing Using the RLCRS

The stripped surfaces of the part were completely free from coating and showed no visual indications of damage. The calculated results of this demonstration are detailed in Table 3-8.

Table 3-8: Results for Assessment of KC-135 Elevator

Parameter	Value
Coating Thickness	3.65 mils
Number of Stripping Passes	3
Total Process Time (including set-up/masking/etc.)	173
Surface Area Stripped	126.00 ft^2
Total Fluence	152.18 J/cm^2
Coating Removal Rate	1.86 ft^2/min
Coating Removal Rate Per mil Coating Removed	6.79 ft^2-mil/min
Total Part Processing Rate	0.73 ft^2/min
Strippable Area	82% of total surface area

3.6.6.4 KC-135 Outboard Aileron

Several condemned KC-135 Outboard Ailerons were available for processing. The ailerons are constructed of a thin-skinned aluminum honeycomb, and one of the available ailerons showed visible signs of delamination of the facesheet from the honeycomb core. Because of this defect, this part was not processed as part of the demonstration. The second outboard aileron that was available showed no visible signs of damage. Pictures of the part prior to laser treatment are provided in Figure 3-11. The coating that was on this part was measured to be 2.86 to 4.13 mils thick (average of measurements is 3.44 mils). The paint system was the standard MIL-PRF-23377 primer and MIL-PRF-85285 topcoat that is normally applied to these parts at OC-ALC. This part had been recently painted by OC-ALC.

Figure 3-11: KC-135 Outboard Aileron Prior To Laser Stripping

Use of the overhead crane was required to move the aileron from its trailer and position it on the parts cart. In total, 10 minutes were spent preparing this part for processing. This part was able to be processed by the RLCRS system by staging each side through 3 positions along its length. Movement of the part to each of these sections was accomplished using the semi-automated parts cart.

Laser stripping of the outboard aileron took 3 passes for each section and totaled 55 minutes for each side. When the positioning and masking steps are included, the part took a total of 120 minutes to process. Pictures of the stripped surfaces are provided in Figure 23.

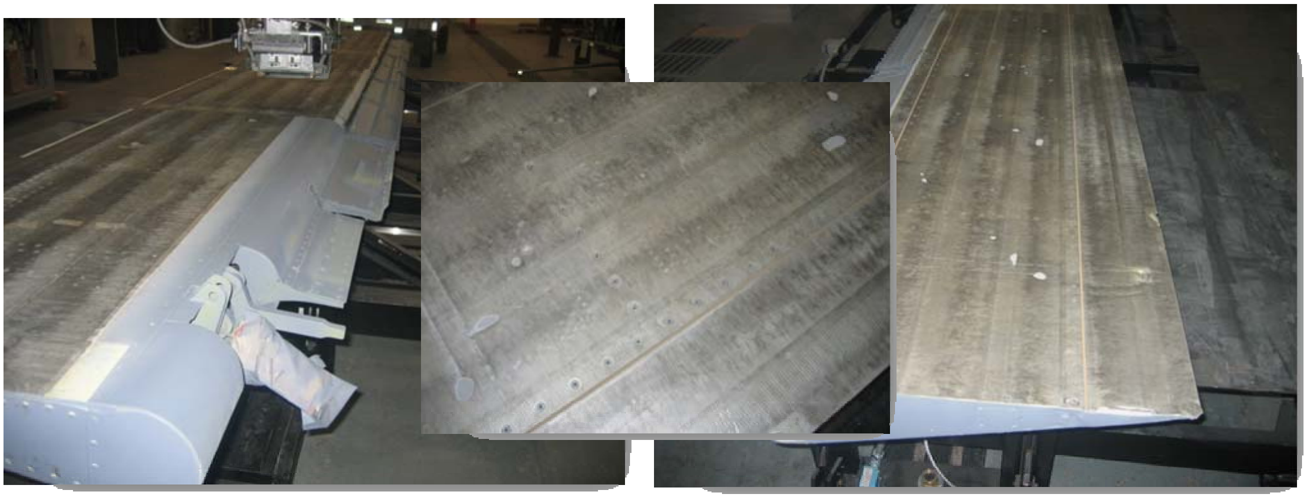

Figure 3-12: KC-135 Outboard Aileron after Processing Using the RLCRS

The stripped surfaces of the part were completely free from coating and showed no visual indications of damage. The calculated results of this demonstration are detailed in Table 3-9.

Table 3-9: Results for Assessment of KC-135 Outboard Aileron

Parameter	Value
Coating Thickness (mils)	3.44 mils
Number of Stripping Passes	3
Total Process Time (min) (including set-up/masking/etc.)	120 minutes
Surface Area Stripped (ft^2)	77 ft^2
Total Fluence (J/cm^2)	139.5 J/cm^2
Coating Removal Rate (ft^2/min)	2.03 ft^2/min
Coating Removal Rate Per mil Coating Removed (ft^2 mil/min)	7.41 ft^2-mil/min
Total Part Processing Rate (ft^2/min)	0.64 ft^2/min
Strippable Area (% of surface area stripped)	73% of total surface area

3.6.6.5 KC-135 Outboard Flap

The final part that was processed during the demonstration testing was a KC-135 Outboard Flap. This part was not an ideal candidate for processing using the RLCRS because there are obstructions on the leading edge of the part and the inside radius is smaller than the RLCRS workhead. The flap does have a fairly large surface area that can be processed, so it is possible that OC-ALC may decide to process this part using the RLCRS combined with other stripping methods.

As with the other parts processed, a condemned flap was obtained and processed. Pictures of the part prior to laser treatment are provided in Figure 3-13. The coating that was on this part was measured to be 2.8 to 3.7 mils thick (average of the thicknesses measured was 3.4 mils). The paint system on this part was not identified, but it consisted of an aged gray topcoat and no primer.

Figure 3-13: Landing Outboard Flap Prior To Laser Stripping

This part is not overly large, but it is heavy. Because of its weight, the use of the overhead crane was required to move the flap from its storage trailer and position it on the parts cart. In total, 10 minutes were spent preparing for processing. This part was able to be processed by the RLCRS system by staging each side through 2 positions along its length. Movement of the part to each of these sections was accomplished using the semi-automated parts cart.

Laser stripping of this part took 3 passes for each section and totaled 65 minutes for each side. When the positioning and masking steps are included, the part took a total of 140 minutes to process. Pictures of the stripped surfaces are provided in Figure 3-14.

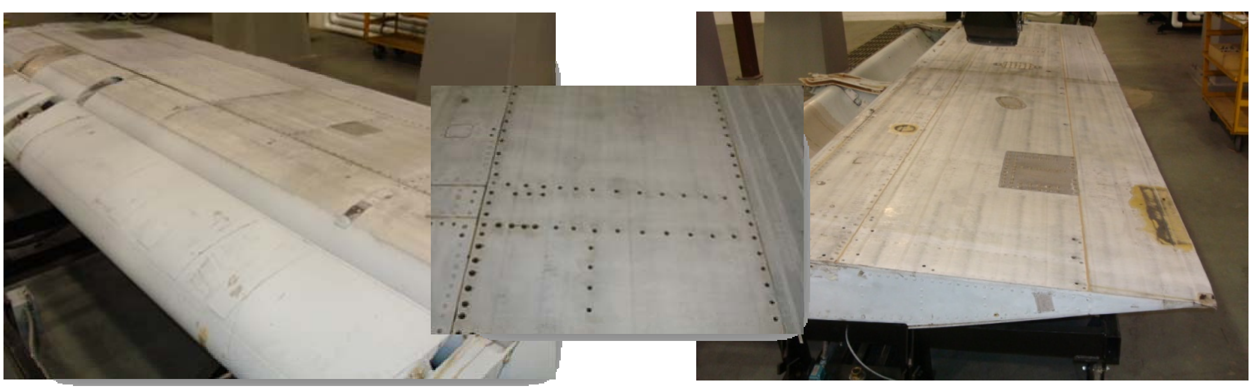

Figure 3-14: KC-135 Outboard Flap after Processing Using the RLCRS

The stripped surfaces of the outboard flap were completely free from coating and showed no visual indications of damage. It would be possible to increase the surface area stripped on the

top side of the part by constructing a small amount of flashing between the leading edge and the main body of the part. This would enable the system to process the concave area in front of the part. The calculated results of this demonstration are detailed in Table 3-10.

Table 3-10: Results for Assessment of KC-135 Outboard Flap

Parameter	Value
Coating Thickness	3.4 mils
Number of Stripping Passes	3
Total Process Time (including set-up/masking/etc.)	140 minutes
Surface Area Stripped	120.00 ft^2
Total Fluence	152.18 J/cm^2
Coating Removal Rate	1.86 ft^2/min
Coating Removal Rate Per mil Coating Removed	6.33 ft^2-mil/min
Total Part Processing Rate	0.86 ft^2/min
Strippable Area	49% of total surface area

3.6.7 Demobilization

The RLCRS system remains at its installation location at OC-ALC for use in production operations. OC-ALC engineering staff is currently working with the KC-135 and E-3 program offices to receive approvals to begin using the RLCRS as part of the standard depainting operations for flight control from these aircraft.

3.7 Selection of Analytical/Testing Methods

Analytical testing procedures were used for the testing of the panels during the screening testing and the parts stripped during the demonstration testing. The various standards that were followed during these tests are provided in Table 3-11.

Table 3-11: Test Requirements

Test Name	Acceptance Criteria	Reference
Screening Testing on Panels		
Aluminum Substrate Assessment		
Strip Rate	N/A. Information purposes only	N/A
Visual Assessment	No visual warping, burning, thermal effects or other damage at 10X magnification	N/A
Substrate Temperature	300°F maximum spike temp	N/A
Superficial Rockwell Hardness	Compare with control sample	ASTM E18
Electrical Conductivity	Compare with control sample	MIL-STD-1537
Tensile Testing	Compare with control sample	ASTM E8
Fatigue Testing	Compare with control sample	ASTM E466
Honeycomb Structural Materials Assessment		
Strip Rate	N/A. Information purposes only	N/A
Visual Assessment	No visual warping, burning, thermal effects or other damage at 10X magnification	N/A
Ultrasonic Inspection of Honeycomb Materials	Compare with control sample	ASTM E114
Peel Resistance	Compare with control sample	ASTM D1781
Flexural Properties	Compare with control sample	MIL-STD-401
Demonstration Testing on Parts		
Coating Strip Rate	N/A. Information purposes only	N/A
Visual Assessment	No visual warping, burning, thermal effects or other damage at 10X magnification	N/A
Substrate Temperature	300°F maximum spike temp (metallic) 200°F maximum spike temp (composite)	SAE MA4872

3.8 Selection of Analytical/Testing Laboratory

Two laboratories were utilized in completing the required testing for the pre-demonstration testing. *CTC*'s laboratories applied the coatings to each of the test panels and performed the visual exams, conductivity tests, ultrasonic tests, and hardness measurements. The Laboratory and Material Services departments at *CTC* were chosen because of their proximity to the RLCRS pre-demonstration site and their capabilities in the coating of test coupons and materials testing.

The AFRL and their support contractor, University of Dayton Research Institute (UDRI), performed all other testing that was required under the JTP including tensile, fatigue, peel resistance, and flexural properties testing. This facility was chosen due to the laboratory's well-established record of material testing.

4.0 PERFORMANCE ASSESSMENT

4.1 Performance Criteria

The general performance criteria that were used to evaluate the performance of the RLCRS are summarized in Table 4-1. These performance criteria have been categorized as either primary or secondary criteria.

Table 4-1: Performance Criteria

Performance Criteria	Description	Primary or Secondary
Product Testing	Must pass individual product tests which include: 1. Visual 2. Substrate Temperature 3. Strippable Area Assessment 4. Processing Time	Primary
Hazardous Materials	RLCRS will reduce or eliminate chemical strippers which contain methylene chloride, VOCs, HAPs, and other undesirable chemicals. The target applications are large off-aircraft components such as elevators, main landing gear doors, flaps, rudders, and ailerons.	Primary
Process Waste	The only waste produced by the RLCRS is the coating material that is removed from the aircraft components.	Primary
Factors Affecting Technology Performance	There are several factors that affect the technology's performance which will all be addressed and optimized during the demonstration: • Laser beam settings and parameters must be set at the optimized conditions for the coating system and substrate • Laser beam stand-off distance from the part or panel must be kept constant (within the allowable error factors) • Proper air flow across the part and evacuation of the debris must be working properly • The laser system, all associated equipment, and the robotic movements must be monitored to insure proper working order	Primary
Reliability	The repeatability of the coating removal operation for various parts will be evaluated, as will the ability of the system to be used continuously without system shut-down	Secondary
Ease of Use	System requires two operators. The operators must receive training on the operation of the equipment and laser safety training. Continuous monitoring of the process is required.	Secondary

Table 4-1: Performance Criteria (cont.)

Performance Criteria	Description	Primary or Secondary
Versatility	RLCRS equipment can be used on any large off-aircraft part that is equal to or smaller than the operating envelope of the equipment. The gantry system is a stationary system and cannot easily be moved.	Secondary
Maintenance	There are regular maintenance intervals for the laser, robot, scanner, and evacuation system. All required maintenance will be documented.	Secondary
Scale-Up Constraints	There are no issues with scale-up since the technology will not need to be scaled-up for full implementation.	Secondary

4.2 Performance Confirmation Methods

This demonstration at OC-ALC was evaluated based upon the results of the panel and parts testing detailed in Table 4-2.

Table 4-2: Expected Performance and Performance Confirmation Methods

Performance Criteria	Expected Performance Metric (pre-demonstration)	Performance Confirmation Method	Actual Performance (post demonstration)
PRIMARY CRITERIA			
Visual Assessment	No visual warping, burning, thermal effects or other damage at 10X magnification	N/A	No visual warping, burning, thermal effects or other damage on aluminum substrates Some burning on magnesium panel that was encountered
Substrate Temperature	300° F peak temperature for aluminum parts	N/A	Temperatures less than 287º F documented in pre-demonstration testing.
Strippable Area Assessment	At least 80% of surface area stripped	N/A	Landing Gear Door: 100% Rudder: 82% Elevator: 82% Outboard Aileron: 73% Outboard Flap: 49%
Total Process Time	Total process times to strip components less than current times.	Record Keeping	Total process times are less than current times.

Table 4-2: Expected Performance and Performance Confirmation Methods (cont.)

Performance Criteria	Expected Performance Metric (pre-demonstration)	Performance Confirmation Method	Actual Performance (post demonstration)
Hazardous Materials	Reduce the use of chemical strippers by 90%. Generate no new hazardous materials.	Record keeping	No chemical strippers used
Process Waste	No new process waste generated	Record keeping	No new waste stream generated
SECONDARY CRITERIA			
Reliability	No breakdowns	Record keeping	No breakdowns.
Ease of Use	Can operate with two people.	Operating Experience	System is operated by two people.
Versatility	Capable of intermittent and long-term operation. Capable of de-coating components other than the chosen candidate parts.	Operating Experience	System is capable of intermittent and long-term operation. System is capable of use on any part that fits within operating envelope of the system.
Maintenance	Regular change of vacuum filters Annual laser preventative maintenance	Operating Experience	No maintenance has been required to date.
Scale-Up Constraints	Not applicable	N/A	N/A

4.3 Data Analysis, Interpretation and Evaluation

This testing was conducted in order to validate the use of the RLCRS for use in coatings removal operations on large components that are removed from aircraft during depot maintenance. Use of this technology would reduce or eliminate DoD dependence on the hazardous chemicals and processes that are currently used to remove coatings. The chemicals that are typically used in this process are high in VOCs and HAPs, which are targeted for reduction/elimination by environmental regulations.

The objective of the screening testing was to verify the ability of the RLCRS to effectively remove common DoD coating systems without causing physical damage to the substrate. The results from this testing provide the DoD with information that can be used to assist in the implementation of laser paint stripping operations at their facilities. The objective of the demonstration testing was to verify the ability of the RLCRS to effectively process the parts that are encountered during depot maintenance operations.

Screening test results indicated that use of the RLCRS has no detrimental effect on 2024 and 7075 aluminum substrates. All testing that was performed on these substrates including superficial hardness, conductivity, tensile testing, and fatigue life showed no degradation in material properties from baseline conditions.

The screening test results show that use of the RLCRS on honeycomb structures causes no detectible defects when visually examined and subjected to ultrasonic inspection. Additionally, the testing showed that the backside of the honeycomb face sheet will not be exposed to temperatures greater than 161°F during processing when the RLCRS is operated at a robotic sweep speed of 3.75 inch/second. Due to defects in the manufacturing of the honeycomb structural test materials comparisons in the effects of the RLCRS on peel resistance and flexural properties cannot be made. It is recommended that additional honeycomb structural test materials be procured and this testing be repeated.

Results from the demonstration testing show that the RLCRS can effectively process a wide variety of parts that are encountered at OC-ALC. The RLCRS system was able to efficiently remove coatings from all of the condemned parts that were processed without causing damage.

Areas of the parts that were not stripped with the RLCRS will be stripped using the handheld laser systems that OC-ALC has qualified for use on KC-135, E-3, and B-52 component parts.
In order to compare the total process time associated with stripping these parts with the RLCRS followed by "nitpicking" using the handheld lasers the manufacturer of the handheld laser reviewed the parts and areas that would require "nitpicking" and provided estimates for performing this nitpicking. Their estimates were based upon an average coating thickness of 5 mils of coating, measurements of the areas of the part that required nitpicking, and the normal removal rates that OC-ALC achieved using their handheld systems. A comparison of the process time required to strip these parts using the RLCRS and handheld laser systems versus the current chemical stripping is presented in Table 4-3.

Table 4-3: Total Process Time Comparison

	Actual RLCRS Process Time (hrs)	Estimated Handheld Laser Process Time (hrs)	Total Process Time of Alternative (hrs)	Current Process Time (hrs)
KC-135 Landing Gear Door	1.6	6	7.6	24
KC-135 Rudder	6.5	6	12.5	48
KC-135 Elevator	2.9	6	8.9	48
KC-135 Outboard Aileron	2	6	8	24
KC-135 Outboard Flap	2.3	9	11.3	24

4.3.1 Air Sampling

During the demonstration, air sampling was performed to determine the levels of potentially hazardous by-products (i.e., the removed coatings) that are not captured by the effluent filtration system during coating removal operations. This sampling was conducted by the OC-ALC Bioenvironmental and Occupational Health Office and all samples were analyzed by the Air Force Institute for Operational Health (AFIOH) laboratory at Brooks City Base, TX. The results of this testing are presented in Table 4-4. Sampling was conducted in the operator booth, in the area where the laser stripping was occurring, and the area outside of the laser coating removal enclosure.

Table 4-4: Air Sampling Results

<table>
<tr><th>Location</th><th>Parameter</th><th>Result (mg/m³)</th></tr>
<tr><td rowspan="13">Inside the Operators Booth</td><td>Hexavalent Chromium</td><td><0.000206</td></tr>
<tr><td>Aluminum</td><td><0.00760</td></tr>
<tr><td>Cadmium</td><td><0.000760</td></tr>
<tr><td>Chromium</td><td>0.00229</td></tr>
<tr><td>Strontium Chromate as Cr</td><td><0.00001</td></tr>
<tr><td>Lead</td><td><0.00380</td></tr>
<tr><td>Lead Chromate, as Cr</td><td><0.00003</td></tr>
<tr><td>Zinc</td><td><0.00760</td></tr>
<tr><td>Zinc Chromate, as Cr</td><td><0.00017</td></tr>
<tr><td rowspan="2">1,6-Hexamethylene Di-Isocyanate (Monomeric)</td><td><0.0186 (15 min exposure)</td></tr>
<tr><td><0.01059 (79 min exposure)</td></tr>
<tr><td rowspan="2">1,6-Hexamethylene Di-Isocyanate (Oligomeric)</td><td><0.0168 (15 min exposure)</td></tr>
<tr><td><0.00957 (79 min exposure)</td></tr>
<tr><td rowspan="13">Inside the Laser Room</td><td>Hexavalent Chromium</td><td><0.000193</td></tr>
<tr><td>Aluminum</td><td><0.00751</td></tr>
<tr><td>Cadmium</td><td>0.00109</td></tr>
<tr><td>Chromium</td><td><0.00150</td></tr>
<tr><td>Strontium Chromate as Cr</td><td><0.00001</td></tr>
<tr><td>Lead</td><td><0.00376</td></tr>
<tr><td>Lead Chromate, as Cr</td><td><0.00002</td></tr>
<tr><td>Zinc</td><td><0.00751</td></tr>
<tr><td>Zinc Chromate, as Cr</td><td><0.00016</td></tr>
<tr><td rowspan="2">1,6-Hexamethylene Di-Isocyanate (Monomeric)</td><td>0.0536 (15 min exposure)</td></tr>
<tr><td>0.04904 (80 min exposure)</td></tr>
<tr><td rowspan="2">1,6-Hexamethylene Di-Isocyanate (Oligomeric)</td><td><0.0171 (15 min exposure)</td></tr>
<tr><td><0.00899 (80 min exposure)</td></tr>
</table>

Table 4-4: Air Sampling Results (continued)

Location	Parameter	Result (mg/m3)
Outside the Laser Room	Hexavalent Chromium	<0.000193
	Aluminum	<0.00736
	Cadmium	<0.000736
	Chromium	<0.00147
	Strontium Chromate as Cr	<0.00001
	Lead	<0.00368
	Lead Chromate, as Cr	<0.00002
	Zinc	<0.00736
	Zinc Chromate, as Cr	<0.00016
	1,6-Hexamethylene Di-Isocyanate (Monomeric)	<0.0182 (15 min exposure)
		<0.01038 (79 min exposure)
	1,6-Hexamethylene Di-Isocyanate (Oligomeric)	<0.0165 (15 min exposure)
		<0.00745 (79 min exposure)

All of these results were within allowable ranges, but two of the readings were slightly above normal and require action. The concentration of monomeric 1,6-Hexamethylene Di-Isocyanate could potentially exceed the 8 hour Occupational Exposure Limit (OEL) in the laser room during stripping operations. Additionally the levels of carbon monoxide (CO) were approaching the Action Level (1/2 of the OEL) of 12.5 ppm. Concentrations of CO reached 9 ppm in the laser room and 7 ppm inside the operator's booth. CO was not detected in the shop adjacent to the laser room. **All other sampling results were considered to be normal for indoor air.**

There is currently no outside fresh air supplied to the room that houses the RLCRS and the air supplied to the operator booth comes from the RLCRS environment. The OC-ALC Bioenvironmental group has recommended that the installation of appropriate ventilation to the RLCRS room and separate ventilation to the operator booth will resolve the elevated readings of Di-Isocyanate and CO. Until the fresh air ventilation is installed the operators of the system will be required to wear respirators. OC-ALC has initiated plans to install the required ventilation.

When moving or touching the parts, the operators are required to wear cotton gloves and an apron to protect against grease, oils, fuels, hydraulic fluids, dirt, and residual coating debris/dust.

During routine maintenance, a half-face respirator and gloves are required when replacing the air filtration system filter bags.

5.0 COST ASSESSMENT

5.1 Cost Reporting

The primary objective of the cost assessment is to determine whether RLCRS can be implemented with an acceptable payback period. An economic analysis was conducted using the Environmental Cost Analysis Methodology (ECAM^{SM}) (reference 7) cost estimating tool, comparing the current chemical depainting process of KC-135 off-aircraft parts that is performed at OC-ALC (Baseline Scenario) to the purchase and installation of a robotic laser coating removal system (Alternative Scenario). Information regarding the costs associated with the current chemical stripping operations at OC-ALC was obtained through a standard questionnaire and gathered during a site visit. This information was then entered into the Environmental Protection Agency's (EPA) pollution prevention cost accounting software, P2 Finance (reference 8) according to the ECAM. This software performs the calculations for payback period, net present value (NPV), and internal rate of return (IRR).

For this cost assessment, the candidate RLCRS was assumed to replace the current chemical stripping process for the selected KC-135 off-aircraft parts (ailerons, rudder, flaps, elevators, and landing gear doors) that is performed at OC-ALC. Since the RLCRS is unable to strip the bracket areas and extreme curvatures of the parts, it was assumed that a portable handheld laser system would perform the coating removal of these areas.

The chemical stripping of the selected parts was targeted as the initial process for implementation of the laser system; however, the candidate laser systems can potentially be utilized on many more applications throughout the depots. For example, the RLCRS may replace chemical stripping, media blasting, and/or hand sanding applications on other large off-aircraft parts from other airframes such as the B-52, E-3, and B-1.

The following general assumptions were made to complete the cost analysis shown in Table 5-1. All calculations and assumptions are available in Appendix A of this report.

- A rate of $236 per hour was assumed for all types of labor, regardless of geographic location or specific skill requirements. This is a fully burdened rate that was provided by HQ AFMC.
- Baseline chemical stripping requires three people per shift, three shifts per day based on assumptions provided by OC-ALC
- RLCRS would require two operators per shift for three shifts per day
- Environmental Health and Safety (EHS) costs (permitting and reporting) for RLCRS would be the same as the current process; therefore, EHS issues were not factored into the cost analysis
- Facility utilities (i.e., lighting, heating, etc.) will not change with the installation of the RLCRS
- Nitpicking step would be performed using a portable handheld laser system

- Capital costs of the portable handheld system would not be considered with the RLCRS capital costs since OC-ALC currently has a portable laser system

Table 5-1: Cost Analysis for Baseline and Alternative Scenarios

Category	Input Parameter	Baseline Scenario Current Chemical Strip	Alternative Scenario RLCRS
Direct Environmental Process Costs			
Start-Up Costs (one-time fees)	Equipment Cost	$0	$819,982
	Installation Cost	$0	$79,384
	One-Time Engineering Cost[1]	$0	$1,027,471
	Training of Operators	$0	$5,660
	Total Capital/Start-Up Costs	**$0**	**$1,932,497**
Labor	Labor to Strip Parts	$9,558,000	$2,152,000
	Lost Labor for Maintenance Downtime	$2,260	$28,300
	Total Annual Labor Costs	**$9,560,260**	**$2,180,300**
Materials	Chemicals	$77,000	$0
	Alkaline Soap	$5,000	$0
	Personal Protective Equipment (PPE)	$30,000	$410
	Masking Materials	$2,000	$84
	Equipment Maintenance Consumables	$0	$19,916
	Total Annual Material Costs	**$114,000**	**$20,410**
Utilities	Rinse Water	$4,300	$0
	Electricity for Equipment	$0	$2,500
	Total Annual Utility Costs	**$4,300**	**$2,500**
Waste	Waste Rinse Water	$20,250	$0
	Trench Cleanout by Contractor	$32,000	$0
	Filters	$1,760	$22
	Paint Chips in Water	$3,440	$0
	Paint Chips from Stripper	$520	$0
	Contaminated Rags & Debris	$2,150	$108
	Total Annual Waste Costs	**$60,120**	**$130**
Indirect Environmental Costs			
EHS / Waste	Reporting Requirements, Documentation Maintenance, etc.	Will not change	Will not change
	OSHA/EHS Training[2]	$0	$1,180
	Medical Exams (Eyes)[3]	$0	$1,180 (one-time)
	Set-Up Waste Streams[4]	$0	$940 (one-time)
	Adjusted Environmental Compliance Recurring Cost	$8,000	$2,200
	Annual Indirect Costs	**$8,000**	**$3,380 ($5,500 first year)**

1. This is the engineering cost for this demonstration only. A subsequent system is expected to require half of the engineering time which equals a cost of approximately $510,000.
2. Other annual training is required (i.e., safety training, hazardous waste training, etc.) and would not change with the new process. Annual laser training is required for Alternative Scenario.
3. Medical examinations are required before an individual's initial assignment to laser duties and as soon as practical following termination of duties involving lasers. Periodic examinations are not required under the relevant standards. The exam takes a half hour to complete for each person, which calculates to be $225 in labor hours (0.5 hrs x 9 people x $50.00/hr = $225).
4. The waste streams for the new system must be set up. This is a one-time event. The labor required to accomplish this was calculated to be $200 (4 hrs x 1 person x $50.00/hr = $200).

As shown in Table 5-1, the implementation of the RLCRS results in a labor savings of approximately $7,400,000, an annual materials cost savings of approximately $113,600, and a waste management cost avoidance of approximately $60,000. The total annual operating cost savings equals approximately $7,500,000.

It is estimated that other Air Force depot facilities, as well as other DoD facilities, that perform chemical depainting of large off-aircraft parts will also realize similar cost savings. For example, if similar cost savings were assumed at all three of the major Air Force depots that perform chemical depainting operations on aircraft parts, the combined cost estimates would result in labor savings of approximately $66,600,000, an annual materials cost savings of approximately $1,000,000, and a waste management cost avoidance of approximately $540,000, and a total annual cost avoidance of approximately $67,000,000 in cost savings.

In addition to cost savings, implementation of the RLCRS will also reduce worker exposure to hazardous chemicals and/or substances. For this cost assessment specifically, with the replacement of the chemical stripping with the laser system, the hazardous chemical strippers are eliminated, and, as a result, the worker's exposure to those hazardous chemicals are also eliminated.

5.2 Cost Analysis

A life cycle cost analysis was performed using the data from Table 5-1 to evaluate the decision of whether a robotic laser coating removal system is a viable alternative to current chemical stripping process for large off-aircraft components. Per ECAM guidance (reference 7), this approach:

- Estimates the annual cash flows using the cost data described above,
- Discounts future cash flows (per Office of Management and Budget (OMB) Circular No. A-94: *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs*, rev. 1/2000) for the time value of money,
- Calculates financial performance measures such as NPV and IRR, and
- Compares these measures with acceptance criteria.

This evaluation was begun by determining the life cycle cost associated with implementation of the RLCRS at OC-ALC. This was calculated by totaling the initial investment required as well as the operating, maintenance, and repair costs expected over the 15 year life of the equipment. A summary of the life cycle cost and life cycle cost savings that are associated with the RLCRS is provided in Table 5-2.

Table 5-2: Life Cycle Cost Analysis

Technology	Installation Cost	Annual Cost	Life Cycle Cost	Life Cycle Cost Savings
Chemical Stripping	$0	$9,746,680	$146,200,200	--
RLCRS	$1,932,497	$2,206,720	$35,033,297	$111,166,903

Three performance measures for investment opportunities were then considered in the ECAM evaluation: payback period, NPV, and IRR. The payback period is the time period required to recover all of the capital investment with future cost avoidance. NPV takes this investment-return analysis one-step further by calculating the difference between capital investments and the present value of future annual cost benefits associated with the alternatives. This value represents the life-cycle costs associated with each of the alternatives. The IRR is the discount rate at which NPV is equal to zero.

NPV and IRR account for the time value of money, and discount the future capital investments or annual cost benefits to the current year. For this analysis, a study period of 15 years was chosen, and a discount rate of 2.7% was used. This discount rate is based on guidance offered by the OMB of Circular A-94, Appendix C (reference 9). It should be noted that the OMB provides both *real* and *nominal* rates. *Real* interest rates were chosen and extrapolated for a 15-year life cycle lifetime. Table 5-3 shows the calculated 15-year net present value, internal rate of return, and discounted payback period for the RLCRS system.

Table 5-3: ECAM Economic Analysis Results

	15 Years
Net Present Value (NPV) Savings	$90,000,000
Internal Rate of Return (IRR)	390%
Discounted Payback Period	0.3 years

Table 5-4 summarizes the investment criteria that were used to compare the capital costs of the proposed RLCRS to the estimated discounted future savings resulting from its replacement of existing coating removal processes.

Table 5-4: Summary of Investment Criteria

Criteria	Recommendations/Conclusions
NPV > 0	Investment return acceptable
NPV < 0	Investment return not acceptable
Highest NPV	Maximum value to the facility
IRR > discount rate	Project return acceptable
IRR < discount rate	Project return not acceptable
Shortest payback period	Fastest investment recovery and lowest risk

Adapted from *ECAM Handbook*.

When comparing the investment criteria in Table 5-4 to the economic analysis results in Table 5-3, it shows that the NPV is positive, the IRR is higher than the 2.7% real discount rate that was used for the financial evaluation, and the discounted payback period of 0.3 years is extremely

short. All of these factors indicate that the investment is acceptable, low risk, and will provide a fast investment recovery. These results support the decision to implement the RLCRS process.

The major cost drivers that promote the implementation of the RLCRS process include the reduced operational labor costs, direct material costs, and waste disposal costs.

5.2.1 Sensitivity Analysis

A sensitivity analysis was performed to investigate realistic scenarios that reveal the sensitivity of the total costs to the major cost drivers which include operational labor, direct materials and waste disposal.

The first cost driver investigated was the operational labor. Concerning the baseline process, the number of operators associated with the stripping of the target components was based on percentages provided by OC-ALC. Taking into account the accuracy of the information provided, the number of operators could realistically vary between two to four people per shift. This would result in labor costs between $6,400,000 to $12,700,000 per year and a payback period between 0.45 to 0.19 years. When investigating the operational labor for the alternative process, the least accurate piece was the handheld laser coating removal stripping time, which was based on a 5 mil coating thickness and time estimates/calculations performed by the laser manufacturer. The coating thickness could realistically vary between 3 mils to 10 mils for the candidate parts. This would result in labor times for the nitpicking process to vary between 1,397 hours to 4,657 hours, which would result in total labor costs for the alternative process to be between $1,930,000 to $2,700,000 per year and a payback period of 0.26 to 0.28 years. Overall, the sensitivity of the operational labor on the payback period is not that significant since the payback period for the worst case scenario associated with the operational labor costs would still be less than a year.

The second cost driver investigated was the combination of direct material and waste disposal costs. These two factors are directly proportional (i.e., when material usage increases, the waste disposal associated with those materials also increases and vice versa) and, therefore, must be considered together. For the baseline process, because the information provided and/or calculated was based in part on percentages, the direct material costs could realistically vary between $75,000 and $140,000, and waste disposal costs could vary between $35,000 and $80,000 per year. This would result in a payback period range of 0.26 to 0.27 years, which shows that these cost drivers are not very sensitive. For the alternative process, the least accurate variable is the waste disposal since the waste disposal sites have not yet been set up by OC-ALC. These costs could realistically range between $100 to $1,000 per year. This would result in no variance in payback period, therefore, showing that the total costs are not sensitive to this cost driver.

Overall, the sensitivity analysis shows that there is little to no change in payback period with respect to the cost drivers investigated. The one aspect that has the ability to significantly affect the total costs and financial analysis is the labor dollar rate. The value provided by the

Headquarters Air Force Materiel Command (HQ AFMC) was $236 per hour; however, if this value changed, it would change the payback period. For example, any dollar amount over $236 per hour would positively impact the cost benefit of implementing the RLCRS. Any dollar amount under $236 per hours would start negatively impacting the cost benefit of implementing the RLCRS. At a $50 per hour labor rate, the cost benefit would still be in favor of implementing the RLCRS with an NPV of $18,800,000, an IRR of 88%, and a payback period of 2.5 years.

6.0 IMPLEMENTATION ISSUES

6.1 Environmental Permits

No new or additional permits are required for the operation of the RLCRS

6.2 Other Regulatory Issues

The current federal regulation governing the safe use of lasers is U.S. Code of Federal Regulations (CFR), Title 21, Part 1040.10. Due to the limited quantity of hazardous waste generated during the use of lasers in coating removal applications, current environmental regulations are not relevant. There are, however, standards for the safe use of lasers with general text to cover all applications. The ANSI document 136.1-1993 is the guidance document for the Military Services and NASA laser safety standards. ANSI 136.1-1993 contains detailed information on the classification of lasers as well as safe handling procedures and health effects from exposure. The Air Force, Navy, and NASA have their own standards as illustrated in Table 6-1.

Table 6-1: Agency and Laser Safety Standard

Agency	Standard
Air Force	Air Force Occupational Safety and Health (AFOSH) Standard 48-139
NASA	NASA Guidelines for Laser Safety (Chapter 8)
Navy	SPAWAR Instructions 5100.12B

In addition, the OSHA promulgated an instruction standard, PUB8-1.7, as a guideline for laser safety and hazard assessment. Some states and local governments have passed legislation concerning the use and safety of lasers. Ten states have passed comprehensive laser regulations. These states are Alaska, Arizona, Arkansas, Florida, Georgia, Illinois, Massachusetts, New York, Texas, and Washington. An outline of the features of each states' legislation is addressed in an article by R.J. Rockwell and J. Parkinson in the Journal of Laser Applications dated October 1999 (Volume 11. Number 5). This article focuses on laser pointers, but offers some insight into the attention states have and might be planning to put on this technology.

Environmental concerns associated with the use of lasers in this application are due to the by-products and emissions generated when coatings are removed. Each type of coating has the potential to produce different types of waste emissions. Until the components of the emissions are identified, they should be characterized as hazardous. Any particulate waste generated should also be characterized as hazardous until properly identified as non-hazardous. Laser operators should be properly fitted with personal protective equipment in accordance with OSHA 29 CFR 1910.134 - *Personal Protective Equipment-Respiratory Protection* and OSHA 29 CFR 1910.132 – *Personal Protective Equipment – General Requirements* to protect them from breathing airborne particles and emissions from the ablated paint that is not captured in the vacuum system.

6.3 End-User / Original Equipment Manufacturer (OEM) Issues

A critical aspect associated with the validation of the RLCRS technology for replacement of chemical stripping is the involvement of the stakeholder community throughout the project. Because of the success of the PLCRS program, which demonstrated handheld laser coating removal for small areas, the relevant stakeholders had already been identified and involved throughout this effort to include the development of the JTP and other requirements for qualification. The stakeholders for this task are listed in Table 6-1 below.

Table 6-2: Demonstration Stakeholders

U.S. Air Force	William Cain	OC-ALC
	Randel Bowman	OC-ALC
	Debora Naguy	AFMC/A4B
	Tom Naguy	AFRL/MLSC
U.S. Navy	Kyle Russel	NAVAIR
	Brad Youngers	NAVAIR

The issues that were relevant to the depots and OEMs in addition to the acceptance criteria established in the JTP are the same performance criteria mentioned in Table 4-2 of this report. A successful debugging/optimization of the RLCRS technology at *CTC* laid foundation for a successful demonstration of the technology at OC-ALC and for acceptance of the technology by the Weapon System Program Offices.

7.0 REFERENCES

1. Heinemann, S. Evaluation of Laser Gantry System. Fraunhofer USA Center for Laser Technology: Plymouth, MI. August 2005

2. Headquarters Air Force Materiel Command Depot Modernization and Logistics Environmental Office. Portable Handheld Laser Small Area Supplemental Coatings Removal System Final Report. Wright-Patterson Air Force Base, OH. 17 August 2005.

3. Hunter, C. Characterization of Pulsed CO2 Laser-Stripped Conversion-Coated Al-Clad 2024-T3 Test Panels. Wright-Patterson Air Force Base, OH. Report No. 03-004. 31 January 2003.

4. Reutzel, E.W. and Sills, C.A. An Investigation of Laser Based Coating Removal. International Congress on Lasers and Electro Optics Conference (ICALEO) 1999 Proceedings.

5. Walters, C.T. Draft Test Plan for RLCRS Operational Readiness and Process Optimization Tests (RLCR-1). Craig Walters Associates: Dublin, OH. 2 August 2006.

6. Concurrent Technologies Corporation. Draft Joint Test Protocol for the Robotic Laser Coating Removal System (RLCRS) Task. Contractor Report FA8601-05-F-0011. Task Order ID 018. June 2006.

7. Air Force Research Laboratory.ESTCP Demonstration Plan for Debugging/Optimization. Wright-Patterson Air Force Base, OH. 20 April 2007.

8.0 POINTS OF CONTACT

Point Of Contact	Organization	Phone / Email	Role in Project
Timothy Hoehman	Tinker AFB	(405) 736-7757 timothy.hoehman@tinker.af.mil	Co-Principal Investigator
Randel Bowman	OC-ALC	(405) 736-2736 randel.bowman@tinker.af.mil	Principal Investigator
Randall Straw	AFRL (*CTC*)	(937) 255-5598 randall.straw@wpafb.af.mil	AFRL Program Manager
James Arthur	*CTC*	(412) 992-5362 arthurj@ctc.com	*CTC* Program Manager

APPENDIX A

Joint Test Report

Environmental Security Technology Certification Program

Joint Test Report

for

Validation of Robotic Laser Coating Removal System

July 17, 2008

PREFACE

This report was prepared by the Air Force Research Laboratory for the Environmental Security Technology Certification Program.

We wish to acknowledge the invaluable contributions provided by the following organizations involved in the creation of this document:

Oklahoma City Air Logistics Center
Concurrent Technologies Corporation
University of Dayton Research Institute

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EXECUTIVE SUMMARY

The processes that are currently used throughout the Department of Defense (DoD) to remove coatings result in a major waste stream consisting of toxic chemicals, spent media blast materials, and waste water. The chemicals that are typically used in this process are high in volatile organic compounds (VOC) and hazardous air pollutants (HAP). When abrasive blast media are used instead of chemical methods, a large quantity of hazardous waste, which is subject to high disposal costs and scrutiny under environmental regulations, is produced.

The use of laser energy for coatings removal is an alternative technology that is environmentally acceptable and less labor intensive than current removal methods. Laser coating removal is a non-intrusive, non-kinetic energy process that can be applied to a variety of substrates, including composites, glass, metal, and plastics. The high level absorption of energy at the surface of a coating material results in the decomposition and removal of the coating. The energy that is applied by the laser is mostly absorbed and utilized in coating decomposition (i.e., instant evaporation, which carries away most of the radiation energy); therefore, the substrate experiences only a minimal increase in temperature.

Oklahoma City Air Logistics Center (OC-ALC), Air Force Research Laboratory (AFRL), and Concurrent Technologies Corporation (*CTC*) have jointly demonstrated and validated a Robotic Laser Coating Removal System (RLCRS) as an alternative technology to the current chemical and mechanical coating removal methods that are used on large off-aircraft components during depot maintenance. This demonstration was performed in order to verify the ability of the RLCRS to effectively remove common DoD coating systems without causing substrate damage. The results from this testing will provide stakeholders with information that will assist in the implementation of automated laser paint stripping operations at their facilities.

The approved Joint Test Protocol (JTP) was followed throughout this demonstration. The JTP contained the critical requirements and tests necessary to qualify the RLCRS for use on metallic substrates. The test results that were achieved during this demonstration indicate that the RLCRS may be used for coating removal applications on metallic substrates without affecting the integrity of the substrate.

1.0 INTRODUCTION

Conventional coatings removal methods that are employed throughout the Department of Defense (DoD) result in a major waste stream consisting of toxic chemicals, spent media blast materials, and waste water. The chemicals that are typically used in this process are high in volatile organic compounds (VOC) and hazardous air pollutants (HAP), both of which are targeted for reduction/elimination by environmental regulations. Coatings removal operations that use abrasive blast media instead of chemical methods result in large quantities of hazardous waste that are subject to high disposal costs and scrutiny under environmental regulations.

A robotic laser coating removal system (RLCRS) has been identified as an alternative technology to supplement the existing depainting processes. A laser is a device that generates monochromatic, coherent light that can be focused and concentrated into a narrow, intense beam of energy. Lasers are already in use by the DoD for multiple manufacturing operations, including welding, cutting, drilling, surface treatment, and small area coatings removal.

Laser coating removal is a non-intrusive, non-kinetic energy process that can be applied to a variety of substrates, including composites, glass, metal, and plastics. The high level absorption of energy at the surface of a coating material results in the decomposition and removal of the coating. Because the applied energy is mostly absorbed and utilized in coating decomposition (i.e., instant evaporation, which carries away most of the radiation energy), the substrate experiences only a minimal increase in temperature.

The objective of this demonstration was to verify the ability of the RLCRS to effectively remove common DoD coating systems without causing physical damage to the substrate. The results from this testing will provide stakeholders with information that will assist in the implementation of laser paint stripping operations at their facilities.

A Joint Test Protocol (JTP) was developed and followed throughout this demonstration. The JTP contained the critical requirements and tests necessary to qualify the RLCRS for use on metallic substrates. All tests were derived from engineering, performance, and operational impact (supportability) requirements that were defined by a consensus of government and industry participants.

This Joint Test Report (JTR) documents the results of the testing, as well as any testing modifications, that were made during the execution of testing. Therefore, this JTR is available as a reference for future pollution prevention endeavors by DoD and commercial users to minimize duplication of effort.

The Environmental Security Technology Certification Program (ESTCP) sponsored funding for the demonstration/validation of this technology, as well as the creation of the JTP and JTR.

2.0 ENGINEERING AND TESTING REQUIREMENTS

A joint group led by Oklahoma City Air Logistics Center (OC-ALC), the ESTCP Project Lead, and technical representatives from Air Force Research Laboratory (AFRL), Naval Air Systems Command (NAVAIR), Concurrent Technologies Corporation (*CTC*) and other government technical representatives identified application, performance, supportability, and operational impact requirements that were relevant to coatings removal applications. The group then reached a consensus on the test procedures, methodologies, and acceptance criteria for each test.

Tests were conducted in a manner that eliminated duplication and maximized the use of each test coupon. For example, where possible, more than one test was performed on each panel. The amount and type of tests that were run on any one panel were determined by the destructive nature of the test.

2.1 ENGINEERING AND TEST REQUIREMENTS

The overall objective of the JTP was to evaluate the performance of the candidate RLCRS for complete removal of selected coating materials. To achieve this objective, the JTP was structured into two categories:

> **Screening Tests** are tests that were performed on flat test panels after the panels were de-coated using the RLCRS. Screening tests were performed at *CTC* and at the AFRL mechanical testing laboratories operated by the University of Dayton Research Institute (UDRI).
>
> **Demonstration Tests** are tests that were performed on off-aircraft parts. The demonstration testing was performed at OC-ALC.

The test requirements that were identified in the JTP for validating the RLCRS are detailed in **Table 1**. These procedures and plans may be found in the *Joint Test Protocol for Validation of a Robotic Laser Coating Removal System*. This listing includes the test name, applicable acceptance criteria, and the references, if any, that were used in developing the tests.

Table 1. Test Requirements

Test Name	Acceptance Criteria	Reference
Screening Testing		
Aluminum Substrate Assessment		
Removal Rate	N/A. Information purposes only	N/A
Visual Assessment (Warping/Denting)	No visual warping, burning, thermal effects or other damage at 10X magnification	N/A
Substrate Temperature	300°F maximum spike temperature	N/A
Superficial Rockwell Hardness	Compare with control sample	ASTM E18
Electrical Conductivity	Compare with control sample	MIL-STD-1537
Tensile Testing	Compare with control sample	ASTM E8
Fatigue Testing	Compare with control sample	ASTM E466
Honeycomb Structural Materials Assessment		
Removal Rate	N/A. Information purposes only	N/A
Visual Assessment	No visual warping, burning, thermal effects or other damage at 10X magnification	N/A
Ultrasonic Inspection	Compare with control sample	ASTM E114
Peel Resistance	Compare with control sample	ASTM D1781
Flexural Properties	Compare with control sample	MIL-STD-401
Demonstration Testing		
Coating Strip Rate	N/A. Information purposes only	N/A
Visual Assessment	No visual warping, burning, thermal effects or other damage at 10X magnification	N/A
Substrate Temperature	300°F maximum spike temperature	SAE MA4872

Several tests that were originally specified in the JTP were eliminated because they were related to the assessment of composite substrates. It was later determined that OC-ALC would not be using the system on composite substrates. As a result, it was decided that efforts would be focused on pursuing validation of the RLCRS only on metallic substrates.

A test of the surface temperature of the back of the face sheet on honeycomb structural materials was added to the screening testing. This test is described in the following subsection.

2.1.1 SUBSTRATE TEMPERATURE: HONEYCOMB STRUCTURAL MATERIALS

<u>Test Description</u>

This procedure assists in determining the peak temperature that the face sheet reaches during the coating removal process. Thermocouples were used to monitor substrate temperature response during the laser stripping process.

Rationale

Temperature response to the coating removal process is critical in determining potential mechanical or physical property degradation of the immediate substrate or internal components.

Test Methodology

Eight sections of the honeycomb structural material will be cut out to reveal the back side of the face sheet. Thermocouples will be mounted on the back of the face sheet with conductive adhesive at the center of each cut out section. The peak temperatures will be recorded.

Parameters	Record temperature readings from all thermocouples and temperature indicator labels.
Panels	One (1) panel with the 0.010 inch face sheet thickness One (1) panel with the 0.016 inch face sheet thickness
Trials Per Panel	Record temperature readings from thermocouples
Acceptance Criteria	< 180°F maximum spike condition.

Data Analysis

Record thermocouple readings during entire stripping process. Report peak temperatures.

Major or Unique Equipment

Thermocouples

3.0 ALTERNATIVE TESTED

The RLCRS that was evaluated was developed specifically for removal of coatings from large off-aircraft weapon system components. This system was designed, assembled, and tested by a team consisting of representatives from OC-ALC, AFRL, and *CTC*. The RLCRS is based on an existing gantry-style robot, but the ultimate goal was not to design a one-of-a-kind system usable on only one specific platform, but rather a system of commercially available off-the-shelf (COTS) components that can be easily integrated into DoD depot operations. This allows individual depots to adapt the technology to meet their specific needs or constraints such as different component configurations or space limitations due to facility sizes.

Assembly and debugging of this system was performed at *CTC* in Johnstown, Pennsylvania. Following debugging at *CTC*, the system was installed at OC-ALC. The RLCRS is made of several subsystems that are integrated together into an automated system. The individual components include the laser, robotic base, beam delivery system, laser scanner, and waste extraction systems.

In order to select an appropriate laser system that would meet the process requirements of large area coating removal, an independent study was commissioned to determine the specifications required for any laser that would be implemented on the RLCRS. This study was performed by the Fraunhofer Institute and was summarized in the report *Evaluation of Laser Gantry* (reference 1). The results of this study were evaluated and compiled into a performance-based Request for Proposal (RFP) that was distributed throughout the laser industry. In response to this RFP, 15 different laser systems (nine carbon dioxide [CO_2], three neodymium: yttrium aluminum garnet [Nd:YAG], and three diode laser systems) were proposed for use in the RLCRS by 10 different laser manufacturers. An intense technical evaluation was performed on these commercial-off-the-shelf (COTS) laser sources and considered the laser specifications, maturity of the laser system, and maintenance requirements for the proposed laser system. At the completion of this evaluation a 6 kilowatt (kW) CO_2 laser from Rofin-Sinar was selected for use in the RLCRS. This laser provides the highest quality laser beam of any of the lasers that were proposed at a power level that is sufficient to rapidly remove coatings without causing excessive heating of the substrate.

The robotic base of the RLCRS system is an existing gantry style robot that was designed and manufactured by PaR Systems, Inc., of Shoreview, Minnesota. This robot was originally manufactured in 1997 as part of a Strategic Environmental Research and Development Program (SERDP) program and was available for this project at no cost. Because of the age of this equipment, a full update of its control system was required. For this update, all control hardware was replaced with a modern Giddings and Lewis MMC motion controller, and a new control software program was created. A non-contact contour following system was also implemented as part of the revised control system. This contour following system allows for the robot to automatically process any part that fits within the operating envelope of the gantry.

The laser beam delivery system transfers the laser output to the work-end of the robot. Because high powered CO_2 lasers cannot be transferred via fiber optic cables, the use of a mirrored beam delivery system was required for the RLCRS system. The beam delivery system for the RLCRS is made up of a nine interlocked beam benders and two telescoping isolation tubes. The entire beam path from the laser source to the work-end of the robot is kept at a slightly positive pressure to prevent the entry of dust or particulates into the beam path during robotic movements. This positive pressure is maintained by purging the beam path with highly purified air.

A manipulation system controls the position of the laser as it moves over the substrate surface. The beam is directed to the target with the appropriate spot size and shape for delivering the energy density required for efficient coating removal. The spot is then rapidly rastered back and forth perpendicular to the direction of robotic movement. For the RLCRS the powerSCAN 2D scanning system was selected. This is a commercially available system with numerous multi-kilowatt installations throughout the U.S, Europe and Asia. A reflective beam focusing module was designed for this application to accommodate the 6 kW power requirements and to produce a 0.7 mm x 7 mm elliptical spot. The elliptical spot geometry was selected to provide a more even overlap pattern as the beam is moved from side to side. The scanning system rasters the beam at a speed of 7 m/s, but there are acceleration/deceleration areas on either side of the scan. To reduce non-uniformity and damage to the substrate in these areas, reflective copper beam blockers were installed to block the beams travel during acceleration/deceleration so that no additional fluence would be received, which can result in substrate heating.

As the coating is volatilized by the laser beam, decomposition by-products enter the laser beam path and are incinerated to produce CO_2, water, inorganic pigment ash, and trace amounts of other compounds. A transverse flow of air in the incineration zone is used to control combustion and collect the effluent. The effluent is swept into a commercially available TEKA Filtercube that collects particulates in its filtration system and exhausts CO_2, water, and trace gases into the atmosphere, and collects particulate matter in conventional filters for future disposal. Because of the incineration, the amount of waste to be disposed represents only a fraction of the original coating volume. For the RLCRS system, the waste collection nozzle includes an air knife to sweep the effluent out of the beam path and into an evacuation duct on the other side to collect the effluent. It is necessary to rapidly sweep all particulate and effluent from the beam path to avoid a reduction in beam irradiance at the surface due to absorption by the effluent. A second air knife was mounted behind the stripping zone and directed to blow straight down at the part surface to provide secondary cooling to the part surface.

4.0 TEST SPECIMEN PREPARATION

4.1 SCREENING TESTING SPECIMENS

Test specimens of various substrates were used during this evaluation to determine the effect that RLCRS use would have on the base material. The test specimens were eighteen (18) inches wide by twenty four (24) inches long and were of various thicknesses. A full description of the various test specimens that were prepared is provided in **Table 2**.

Table 2. Test Panel Substrate Code and Description

Panel Specimen Code	Substrate Description
Al-2a	Aluminum alloy: 2024-T3 (Bare) 24 inch x 18 inch x 0.025 inch. Cleaned according to ASTM F22-02, chromic acid anodized, conforming to MIL-A-8625, (*Anodic Coatings for Aluminum and Aluminum Alloys*, issued September 10, 1993), Type 1B.
Al-2b	Aluminum alloy: 2024-T3 (Bare) 24 inch x 18 inch x 0.025 inch. Cleaned according to ASTM F22-02, chromate conversion coated, conforming to MIL-C-5541E, (*Chemical Conversion Coatings on Aluminum and Aluminum Alloys*, issued November 30, 1990), Class 1A.
Al-2c	Aluminum alloy: 2024-T3 (Clad) 24 inch x 18 inch x 0.025 inch. Cleaned according to ASTM F22-02, chromate conversion coated, conforming to MIL-C-81706/5541E, (*Chemical Conversion Coatings on Aluminum and Aluminum Alloys*, issued November 30, 1990), Class 1A.
Al-7b	Aluminum alloy: 7075-T6 (Bare) 24 inch x 18 inch x 0.025 inch. Cleaned according to ASTM F22-02, chromate conversion coated, conforming to MIL-C-5541E, (*Chemical Conversion Coatings on Aluminum and Aluminum Alloys*, issued November 30, 1990), Class 1A.
MH-a	Aluminum Honeycomb 24 inch x 18 inch Face Sheets: 0.010 inch, 2024-T3 clad Core: 0.625 inch thick, Hexagonal, non-perforated 3/16 inch cell, 0.0020 inch nominal foil, Al alloy 3003-H18 or H19 or optional 5052-H38 or H-39.
MH-b	Aluminum Honeycomb 24 inch x 18 inch Face Sheets: 0.016 inch, 2024-T3 clad Core: .625 inch thick, Hexagonal, non-perforated 3/16 inch cell, 0.0020 inch nominal foil, Al alloy 3003-H18 or H19 or optional 5052-H38 or H-39.

These test specimens were coated with several different paints to evaluate the removal rate of standard DoD coatings. The various combinations of primer and topcoat that were used during this evaluation are listed in **Table 3**.

Table 3. Coating Systems

Coating Code	Primer	Topcoat	Total Targeted Thickness (Primer and Topcoat (mils))
STD	MIL-PRF-23377, Type 1, Class C	MIL-PRF-85285, Type 1, Class H	10
APC	MIL-PRF-23377, Type 1, Class C	Advanced Performance Coating (Deft Extended Life Topcoat)	10
NAV	MIL-PRF-85582, Type 1, Class C	MIL-PRF-85285, Type 1, Class H	10

Each liquid coating system was prepared and applied in accordance with the appropriate specifications. Application was conducted at a minimum temperature of 70° F and 50% ±10% relative humidity (RH). To ensure uniform coating thickness, coating applications were conducted per ASTM D823, *Standard Practices for Producing Films of Uniform Thickness of Paint, Varnish, and Related Products on Test Panels*.

All topcoats were applied over the primer within the manufacturer's recommended time and artificially aged for 7 days at room temperature followed by 7 days at 150° F (±5°). Coating application was performed at the *CTC* Demonstration Factory located in Johnstown, PA.

In order to effectively evaluate the performance of the RLCRS, several variations of baseline panels were prepared. The first set of baseline panels were unprocessed test panels, i.e., tested in the as-shipped condition from the manufacturer. Two panels of each type of material were designated as "baseline" materials.

The second set of baseline panels were only subjected to the artificial aging process that was previously described . These panels were prepared to determine if the artificial aging process had any mechanical effect on the substrates themselves, independent from the coating removal process. These panels were subjected to four (4) cycles of baking and cooling at *CTC*'s Demonstration Factory. Two panels of each of the bare aluminum and honeycomb structures were designated as "baseline-baked" and were subjected to this baking process.

The third and final set of baseline panels was prepared to provide comparison to the current baseline chemical coating removal operations that are performed by OC-ALC. These test panels were stripped in accordance with the de-painting procedures used at the ALCs, which includes 1) spraying the coated test panels with 1-part stripper or Plane Naked™ stripper, 2) allowing the chemical to dwell, and 3) rinsing off the chemical and paint with water. These panels were to be subjected to four (4) cycles of coating application and de-painting. These panels were coated within *CTC*'s Demonstration Factory, and the chemical stripping operations were

performed at OC-ALC by OC-ALC personnel. Several panels of each of the bare aluminum and honeycomb substrates were designated as “baseline –chemical strip” and were subjected to this procedure.

Due to production priorities at the ALC, long delays occurred in the chemical stripping of several of these panels. In order to move forward with mechanical testing of the test specimens, it was decided that tensile testing and fatigue testing would be performed on samples that had only undergone one (1) round of chemical testing. This decision was made because repeated cycles of chemical stripping were not suspected to have an effect on these mechanical properties. Testing of chemically stripped panels that had undergone the full four cycles would be performed if a significant difference of the tensile or fatigue properties was discovered between the chemically stripped, baked, and laser stripped panels.

Lastly, the panels that were used to evaluate the laser stripping process were subjected to four (4) cycles of coating application and de-painting within *CTC*’s Demonstration Factory.

4.2 DEMONSTRATION TESTING SPECIMENS

Several condemned KC-135 aircraft parts were obtained for use in the demonstration testing. These parts were removed from the condemned airframes and represented the base set of parts that the RLCRS was designed to process. Specifically, the following parts that were obtained included the following:

- KC-135 Landing Gear Door
- KC-135 Rudder
- KC-135 Elevator
- KC-135 Outboard Aileron
- KC-135 Outboard Flap.

5.0 SCREENING TEST RESULTS

An overview of the results of the screening testing that was conducted is presented in **Table 4**. A description of each of the test procedures that were followed, the testing methodologies, and a discussion of the results of each test are provided in the following sections.

Table 4. Data Summary

Performance Criteria	Baseline	Baseline Baked	Laser Stripped	Chemically Stripped	Acceptance Criteria
Coating Strip Rate (ft^2/min)					
2024 Al – Bare	n/a	n/a	1.0	n/a	Information purposes only
2024 Al - Clad	n/a	n/a	1.0	n/a	
2024 Al – Anodized	n/a	n/a	0.8	n/a	
7075 Al – Bare	n/a	n/a	1.0	n/a	
Aluminum Honeycomb 0.010” Face Sheet	n/a	n/a	0.9	n/a	
Aluminum Honeycomb 0.016” Face Sheet	n/a	n/a	0.9	n/a	
Visual Damage Assessment					
2024 Al – Bare	No surface abnormalities	No surface abnormalities	No surface abnormalities	No surface abnormalities	No visual warping, burning, thermal effects or other damage at 10X magnification
2024 Al - Clad	No surface abnormalities	n/a	No surface abnormalities	n/a	
2024 Al – Anodized	No surface abnormalities	n/a	Warping, burning of anodize layer	n/a	
7075 Al – Bare	No surface abnormalities	No surface abnormalities	No surface abnormalities	No surface abnormalities	
Aluminum Honeycomb 0.010” Face Sheet	No surface abnormalities	No surface abnormalities	No surface abnormalities	No surface abnormalities	
Aluminum Honeycomb 0.016” Face Sheet	No surface abnormalities	No surface abnormalities	No surface abnormalities	No surface abnormalities	
Substrate Temperature (°F)					
2024 Al – Bare	n/a	n/a	271° F	n/a	300° F max for aluminum 180° F max for honeycomb
2024 Al - Clad	n/a	n/a	287° F	n/a	
2024 Al – Anodized	n/a	n/a	248° F	n/a	
7075 Al – Bare	n/a	n/a	261° F	n/a	
Aluminum Honeycomb 0.010” Face Sheet	n/a	n/a	161° F	n/a	
Aluminum Honeycomb 0.016” Face Sheet	n/a	n/a	160° F	n/a	
Superficial Hardness (HR15T)					
2024 Al – Bare	83.0	83.4	82.9	82.8	Compare with baseline sample
7075 Al - Bare	88.4	88.8	88.7	89.0	
Electrical Conductivity (%IAC)					
2024 Al – Bare	30.2	30.1	30.1	30.0	Compare with baseline sample
7075 Al - Bare	32.0	32.2	32.1	32.2	

Table 4. Data Summary (continued)

Performance Criteria	Baseline	Baseline Baked	Laser Stripped	Chemically Stripped	Acceptance Criteria
Tensile Properties					
Yield Strength (ksi)					Compare with baseline sample
2024 Al – Bare	53.1	52.7	52.7	52.5	
7075 Al - Bare	75.0	75.7	76.0	75.6	
Tensile Strength (ksi)					
2024 Al – Bare	71.4	71.5	71.6	71.3	
7075 Al - Bare	84.7	85.0	84.9	85.0	
Elongation (%)					
2024 Al – Bare	16.4	17.0	16.9	17.1	
7075 Al - Bare	13.7	12.7	12.9	13.2	
Fatigue Properties					
Average Cyclic Life (cycles) – Max Stress 45 ksi					Compare with baseline sample
2024 Al – Bare	312,743	192,281	166,619	184,578	
7075 Al - Bare	93,904	118,372	133,809	64,732	
Average Cyclic Life (cycles) – Max Stress 55 ksi					
2024 Al – Bare	40,562	52,628	40,305	57,941	
7075 Al - Bare	36,764	22,776	32,421	31,320	
Ultrasonic Inspection					
Aluminum Honeycomb 0.010” Face Sheet	No discontinuity	No discontinuity	No discontinuity	No discontinuity	No discontinuity
Aluminum Honeycomb 0.016” Face Sheet	No discontinuity	No discontinuity	No discontinuity	No discontinuity	
Peel Resistance (Average Peel Torque (in-lb$_f$/in))*					
Aluminum Honeycomb 0.010” Face Sheet	23.5	22.8	23.2	25.6	Compare with baseline sample
Aluminum Honeycomb 0.016” Face Sheet	27.9	19.9	27.2	26.1	
Flexural Testing (Average Peak Flexural Load (lb$_f$))*					
Aluminum Honeycomb 0.010” Face Sheet	950	1172	1267	986	Compare with baseline sample
Aluminum Honeycomb 0.016” Face Sheet	1447	1557	1202	1436	

*AFRL/RXSA determined that the panels as manufactured are not representative of structural materials used on flight controls; therefore, no valid conclusions can be drawn from this data set. Peel resistance testing will be redone using new honeycomb structural materials.

5.1 ALUMINUM SUBSTRATE ASSESSMENT

Optimization testing was conducted prior to processing the test panels that were used for the aluminum substrate assessment. This optimization testing was focused on determining the proper settings of the RLCRS control system variables that would allow for maximum strip rate without causing damage to the substrate. As a result of the system optimization, the processing parameters presented in Table 5 were used throughout the aluminum substrate assessment.

Table 5. RLCRS Parameters Used for Aluminum Substrate Assessment

Units Measured	Value
Laser Power	6000 W
Laser Power at surface	4500 W
Focused Spot Size	0.7 mm x 4.5 mm ellipse
Irradiance	102.3 kW/cm^2
Scan Rate	7 m/s
Scan Width	127 mm
Stand-Off Distance	500 mm
Sweep Rate – bare, clad panels	1.75 in/s
Sweep Rate – anodized panels	3.0 in/s

Testing was conducted for removal rate, visual examination, substrate temperature, hardness, electrical conductivity, tensile properties, and fatigue life. Per the approved JTP, the 2024 clad and 2024 anodized panels were only subjected to removal rate and visual examination because previous testing of laser coating removal systems had shown that surface treatments do not have a significant effect on how the laser treatment interacts with the bulk material properties of the substrate.

Also per the approved JTP, the test panels that had been prepared using the APC coating system and the NAV coating system were also only subjected to removal rate and visual examination testing. This was done because the three coating systems are similar enough in composition that there was not expected to be any difference in the effects of laser coating removal on the mechanical properties of the base substrate between the coating systems.

The 2024 bare and 7075 bare substrates that were coated with the MIL-PRF-23377 primer and MIL-PRF-85285 topcoat were subjected to all of the tests specified in the JTP.

5.1.1 ALUMINUM STRIP RATE

Trials were conducted to determine the rate at which each of the coating systems could be removed. The coating strip rate test data that was compiled is based on removing coatings from a test area equal to 3 ft^2.

This test was performed for informational purposes only, and no JTP acceptance criterion was established. During the course of this strip rate testing, the coatings were completely stripped to the substrate. The test results are summarized in **Table 6**. The strip rate reported in this table considers the actual measured thickness of the coating and normalizes the rate to a 10-mil thick coating.

Table 6. Coating Strip Rate Summary

Substrate	Coating System	Round 1 Strip Rate (ft^2/min)	Round 2 Strip Rate (ft^2/min)	Round 3 Strip Rate (ft^2/min)	Round 4 Strip Rate (ft^2/min)	AVERAGE STRIP RATE (ft^2/min)
2024 Al - Bare	MIL-PRF-23377 MIL-PRF-85285	0.9	1.1	1.0	0.8	**1.0**
2024 Al - Bare	MIL-PRF-23377 APC	0.5[a]	1.1	0.9	1.1	**1.0**
2024 Al - Bare	MIL-PRF-85582 MIL-PRF-85285	0.8	1.0	1.0	0.9	**0.9**
2024 Al – Clad	MIL-PRF-23377 MIL-PRF-85285	0.9	1.0	1.1	0.8	**1.0**
2024 Al- Anodized	MIL-PRF-23377 MIL-PRF-85285	0.8	0.8	0.8	0.6 [b]	**0.8**
7075 Al - Bare	MIL-PRF-23377 MIL-PRF-85285	1.0	1.0	1.0	0.8 [b]	**1.0**
7075 Al - Bare	MIL-PRF-23377 APC	1.1	1.1	0.9	1.1	**1.0**
7075 Al - Bare	MIL-PRF-85582 MIL-PRF-85285	1.0	1.0	1.0	1.0	**1.0**

a – laser was misaligned when this panel was processed, data is invalid and not included in the average strip rate calculation
b – the laser chiller was malfunctioning due to a refrigerant leak causing laser to lose power, data is invalid and not included in average strip rate calculation

5.1.2 VISUAL DAMAGE ASSESSMENT OF ALUMINUM PANELS

A visual examination was performed on the test panels at 10X magnification to identify any indication of damage. Each substrate was examined for substrate damage upon receiving the panels from the vendor and after each of the four removal cycles . Any surface abnormalities were noted and photographed. A summary of the visual examination is provided in **Table 7**.

Table 7. Visual Damage Assessment of Aluminum Panels

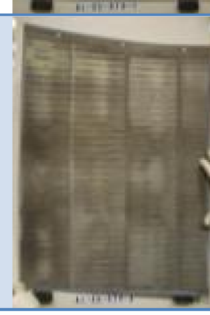
Substrate	Coating System	Results	Typical Surface Picture (no magnification)
2024 Al - Bare	MIL-PRF-23377 MIL-PRF-85285	No surface abnormalities	
2024 Al - Bare	MIL-PRF-23377 APC	No surface abnormalities	
2024 Al - Bare	MIL-PRF-85582 MIL-PRF-85285	No surface abnormalities	
2024 Al – Clad	MIL-PRF-23377 MIL-PRF-85285	No surface abnormalities	
2024 Al- Anodized	MIL-PRF-23377 MIL-PRF-85285	Excessive warping, minor burning of anodized layer	

Table 7. Visual Damage Assessment of Aluminum Panels (continued)

Substrate	Coating System	Results	Typical Surface Picture (no magnification)
7075 Al - Bare	MIL-PRF-23377 MIL-PRF-85285	No surface abnormalities	
7075 Al - Bare	MIL-PRF-23377 APC	No surface abnormalities	
7075 Al - Bare	MIL-PRF-85582 MIL-PRF-85285	No surface abnormalities	

Results of the visual examination were acceptable for all substrate/coating combinations were acceptable except for the panels that were treated with an anodize coating. These panels showed some warping and burning of the anodize layer. This is because the anodize coating absorbs the majority of the laser energy instead of reflecting it as the bare and clad surfaces do. Further refinement of the operating parameters would be required prior to use of the RLCRS system on parts that have anodized surfaces. Because the production parts that OC-ALC has targeted for processing with the RLCRS are not anodized the optimization of the system for use on anodized surfaces was not continued.

5.1.3 DETERMINATION OF SUBSTRATE TEMPERATURE: ALUMINUM

Temperature response to the coating removal process is critical in determining potential mechanical or physical property degradation. In order to determine the peak temperature that the substrate reaches during the coating removal process, thermocouples and adhesive temperature indicator labels were used to monitor substrate temperature response.

After the test panels were coated, twelve (12) Type K thermocouples were mounted on the back of the panel with conductive adhesive at the center of each 6 inch x 6 inch quadrant. Temperature data were collected 10 times a second during the laser stripping operations. **Figure 1** displays a picture of the layout for thermocouple and temperature indicator label placement on the backside of the test panels.

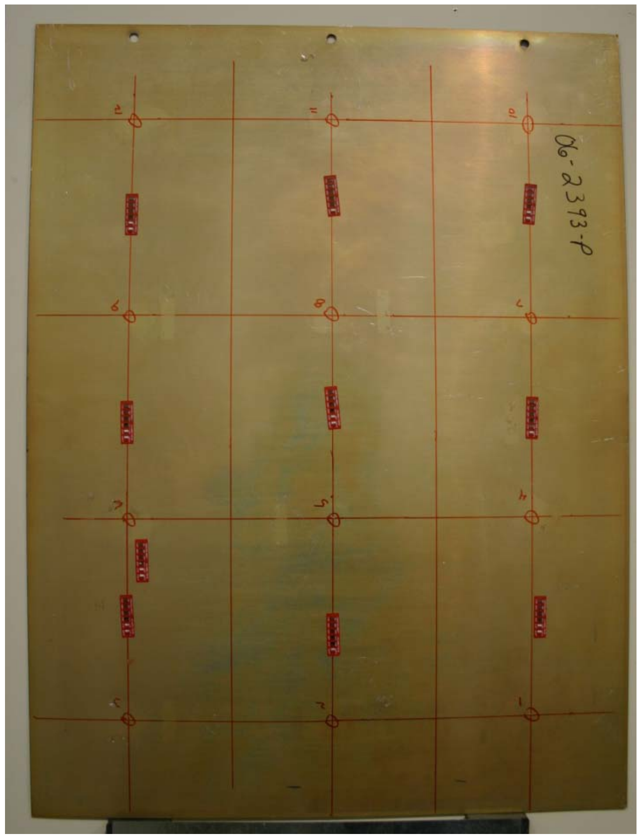


Figure 15. Thermocouple Placement on Aluminum Panels

The acceptance criterion that was established for this test was a maximum temperature spike of 300° F. The maximum recorded temperatures for each of the rounds of coating removal is provided in **Table 8**.

The temperatures that were experienced during the first round of laser stripping slightly exceeded the maximum allowable temperature peak. To correct this slight deviation, a second air knife was added to the RLCRS. This secondary air knife was located directly behind the laser treatment area and directed onto the part surface to cool the substrate during laser stripping operations. This minor modification to the RLCRS allowed for the system to operate within the temperature boundaries that were established for the remaining rounds of coating removal.

It is important to note that the operating parameters for the RLCRS were selected based largely upon the 300° F maximum temperature requirement. If a lower maximum temperature is required, the operational parameters can be easily changed to accommodate the desired temperature, which will result in a slight decrease in stripping rate.

Table 8. Maximum Temperature of Aluminum Panels

Substrate	Coating System	Maximum Temperature °F			
		Round 1	Round 2	Round 3	Round 4
2024 Al - Bare	MIL-PRF-23377 MIL-PRF-85285	*300.8*	226.3	263.6	270.8
2024 Al – Clad	MIL-PRF-23377 MIL-PRF-85285	293.2	244.2	270.1	261.9
2024 Al- Anodized	MIL-PRF-23377 MIL-PRF-85285	293.8	211.7	261.2	247.7[a]
7075 Al - Bare	MIL-PRF-23377 MIL-PRF-85285	*307.0*	255.1	260.5	175.5[a]

a – the laser chiller was malfunctioning due to a refrigerant leak causing the laser to lose power, data is invalid and not included in average strip rate calculation

5.1.4 SUPERFICIAL HARDNESS OF ALUMINUM

Superficial hardness testing was conducted on aluminum substrates following application of the laser depainting process and on the baseline unprocessed, baked, and chemically stripped panels. The hardness values were examined to determine any change in the temper of the alloy. Testing was conducted per ASTM E18, *Standard Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials*. Twelve (12) readings were taken on each panel after each round of coating removal. The average test results are presented in **Table 9**.

Table 9. Average Superficial Hardness Of Aluminum

Substrate	Removal Method	Hardness HR15T *(std. dev.)*			
		Round 1	Round 2	Round 3	Round 4
2024 Al - Bare	None - Baseline	83.0 *(±0.3)*	n/a	n/a	n/a
2024 Al - Bare	None - Baked	83.3 *(±0.2)*	82.7 *(±1.0)*	83.2 *(±0.4)*	83.4 *(±0.4)*
2024 Al - Bare	Chemical	82.6 *(±1.5)*	83.4 *(±0.4)*	83.1 *(±1.0)*	82.8 *(±1.1)*
2024 Al - Bare	Laser	83.0 *(±0.6)*	83.2 *(±0.8)*	82.6 *(±0.7)*	82.9 *(±0.9)*
7075 Al - Bare	None - Baseline	88.4 *(±0.2)*	n/a	n/a	n/a
7075 Al - Bare	None - Baked	89.0 *(±0.2)*	88.4 *(±0.7)*	88.9 *(±0.4)*	88.8 *(±0.3)*
7075 Al - Bare	Chemical	88.4 *(±0.8)*	88.5 *(±0.9)*	89.1 *(±0.5)*	89.0 *(±0.3)*
7075 Al - Bare	Laser	89.2 *(±1.3)*	88.5 *(±1.7)*	88.5 *(±0.2)*	88.7 *(±0.3)*

The data that were collected during this testing was analyzed for statistically significant variations using a single factor analysis of variance. This analysis showed that for the 2024 aluminum there is no statistically significant difference between the superficial hardness results for the baseline panels and those of the laser stripped, chemical stripped, or baked panels. For the 7075 aluminum there is no statistically significant difference between the hardness values of the baseline panels and those that were laser treated, but there is statistical significance between the values recorded for the baseline and the slightly higher values for the baked and chemically stripped sets.

5.1.5 ELECTRICAL CONDUCTIVITY OF ALUMINUM

The electrical conductivity test was performed to assess possible changes in the temper of the substrate caused by high temperatures during the laser coating removal process. Electrical conductivity testing was conducted per MIL-STD-1537, *Electrical Conductivity Test for Verification of Heat Treatment of Aluminum Alloys Eddy Current Method*. Twelve (12) conductivity readings were recorded for each panel after each stripping cycle. The test results are provided in **Table 10**.

Table 10. Average Electrical Conductivity Data

Substrate	Removal Method	Conductivity %IAC *(std. dev.)*			
		Round 1	**Round 2**	**Round 3**	**Round 4**
2024 Al – Bare	None - Baseline	30.2 *(±0.1)*	n/a	n/a	n/a
2024 Al - Bare	None - Baked	30.0 *(±0.0)*	30.0 *(±0.0)*	30.2 *(±0.0)*	30.1 *(±0.0)*
2024 Al - Bare	Chemical	30.1 *(±0.1)*	30.0 *(±0.1)*	30.0 *(±0.0)*	30.0 *(±0.1)*
2024 Al - Bare	Laser	30.1 *(±0.1)*	30.1 *(±0.0)*	30.1 *(±0.0)*	30.1 *(±0.0)*
7075 Al- Bare	None - Baseline	32.0 (±0.1)	n/a	n/a	n/a
7075 Al - Bare	None - Baked	32.2 *(±0.3)*	31.9 *(±0.2)*	32.2 *(±0.2)*	32.2 *(±0.2)*
7075 Al - Bare	Chemical	32.2 *(±0.1)*	31.9 *(±0.1)*	32.2 *(±0.1)*	32.2 *(±0.1)*
7075 Al - Bare	Laser	31.9 *(±0.1)*	32.1 *(±0.1)*	32.0 *(±0.1)*	32.1 *(±0.2)*

The data shows that the laser coating removal process does not have an effect on the electrical conductivity of the aluminum. The results for each of the laser coating removal rounds are within the standard deviation of the baseline panel conductivity readings.

5.1.6 TENSILE TESTING OF ALUMINUM

Tensile testing was performed to determine the extent of damage caused by the laser stripping process in terms of its effect on the yield strength, tensile strength, and elongation of the metal. Tensile testing was performed using an Instron 4505 universal test machine per ASTM E8, *Standard Test Methods for Tension Testing of Metallic Materials*. All testing was performed under displacement control at a rate of 0.1 inch/min until the specimen failed. Specimen strain was obtained during the test using an Instron 2-inch GL extensometer. Ductility, measured as specimen elongation at failure, was determined after the test using the fit-back method as prescribed in the ASTM standard. Five specimens were tested for each of the experimental conditions: unprocessed, baked four times, chemically stripped once, and laser stripped four times. A summary of the tensile testing results is presented in **Table 11**.

Table 11. Average Tensile Property Information

Substrate	Removal Method	Yield Strength ksi *(std. dev.)*	Ultimate Tensile Strength ksi *(std. dev.)*	Elongation % *(std. dev.)*
2024 Al Bare	None	53.1 *(±0.37)*	71.4 *(±0.71)*	16.4 *(±2.3)*
2024 Al Bare	None - Baked	52.7 *(±0.21)*	71.5 *(±0.19)*	17.0 *(±0.6)*
2024 Al Bare	Chemical	52.5 *(±0.30)*	71.3 *(±0.33)*	17.1 *(±0.3)*
2024 Al Bare	Laser	52.7 *(±0.30)*	71.6 *(±0.67)*	16.9 *(±0.6)*
7075 Al Bare	None	75.0 *(±0.64)*	84.7 *(±0.59)*	13.7 *(±0.7)*
7075 Al Bare	None - Baked	75.7 *(±0.53)*	85.0 *(±0.35)*	12.7 *(±0.4)*
7075 Al Bare	Chemical	75.6 *(±0.37)*	85.0 *(±0.20)*	13.2 *(±0.3)*
7075 Al Bare	Laser	76.0 *(±0.77)*	84.9 *(±0.79)*	12.9 *(±0.4)*

A review of the tensile strength data shows that no debits in the strength properties of the aluminum occur from any of the processing that was performed. Average yield strength for the 2024 baseline samples decreased slightly following the four bake cycles, but was within the scatter for the non-baked baseline data. The opposite effect was seen with the 7075 aluminum yield strength data: average yield strength increased slightly following the bake cycle. No change in strength properties were exhibited between the baked panels and those panels that were subjected to chemical or laser stripping. These results are compared to the Metallic Materials Properties Development and Standardization Handbook (MMPDS-03) in terms of "A-allowable" and are presented graphically in **Figure 2** for 2024 aluminum and **Figure 3** for 7075 aluminum.

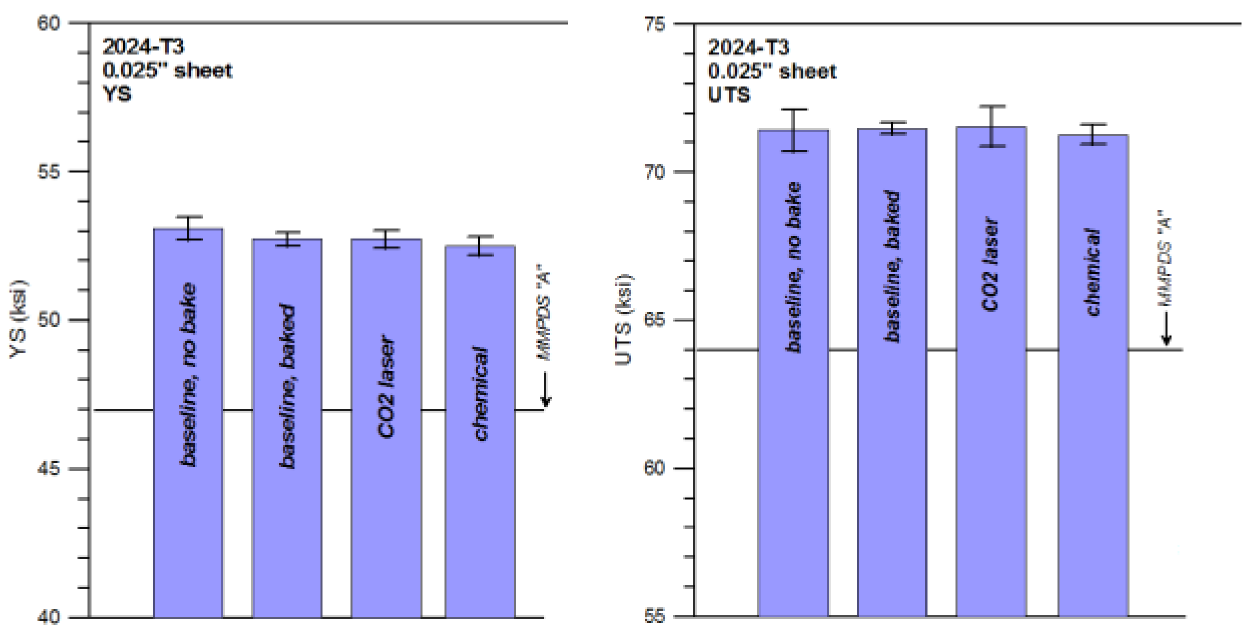


Figure 2. Yield Strength and Tensile Strength of 2024 Aluminum Samples

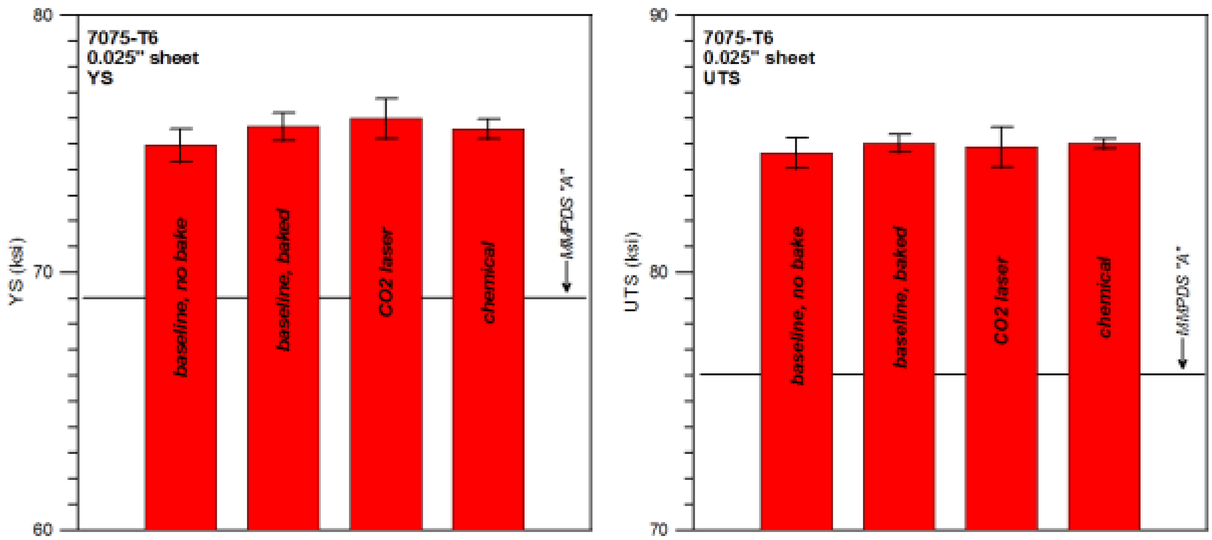


Figure 3. Yield Strength and Tensile Strength of 7075 Aluminum Samples

5.1.7 FATIGUE TESTING OF ALUMINUM

Fatigue testing was performed to assess possible changes in the fatigue life of the substrate caused by high temperatures during the laser coating removal process. Smooth fatigue testing was accomplished using an MTS servo-hydraulic test machine under laboratory air conditions. Testing followed ASTM E466, *Standard Test Method for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials*. MTS model 647 wedge grips were used to grip the samples, and a maximum grip pressure of 500 psi was used. Testing was performed under a sinusoidal load control mode at 30 Hz up to a maximum cycle count of 10,000,000. Alignment accuracy was verified at less than 4% prior to testing. The machined edges of all fatigue specimens were polished longitudinally using 600 grit polishing paper prior to testing to remove measurement machining marks. To ensure that the fatigue results were not compromised, no surface polishing was performed on either of the specimen surfaces.

Five specimens were tested for each of the experimental conditions: unprocessed, baked four times, chemically stripped once, and laser stripped four times.

In order to better assess the change in fatigue performance, it was decided to replicate a low and high stress condition and compare the average lives for each sample population. For the 2024 aluminum samples, tests were run at 45 and 55 ksi maximum stress. The resulting fatigue data is provided in **Table 12** in terms of average fatigue life, maximum fatigue life, and minimum fatigue life for a minimum of 5 tests per condition. This data is also presented graphically in **Figure 4**.

Table 12. 2024 Aluminum Fatigue Data

Removal Method	Max Stress ksi	Average Cycles to Failure	Maximum Cycles to Failure	Minimum Cycles to Failure
None - Baseline	45	312,743	419,002	211,754
	55	40,562	45,766	35,092
None - Baked	45	192,281	226,640	149,018
	55	52,628	57,761	42,575
Chemical	45	184,578	258,484	106,035
	55	57,941	72,978	37,404
Laser	45	166,619	312,033	75,572
	55	40,305	50,110	33,930

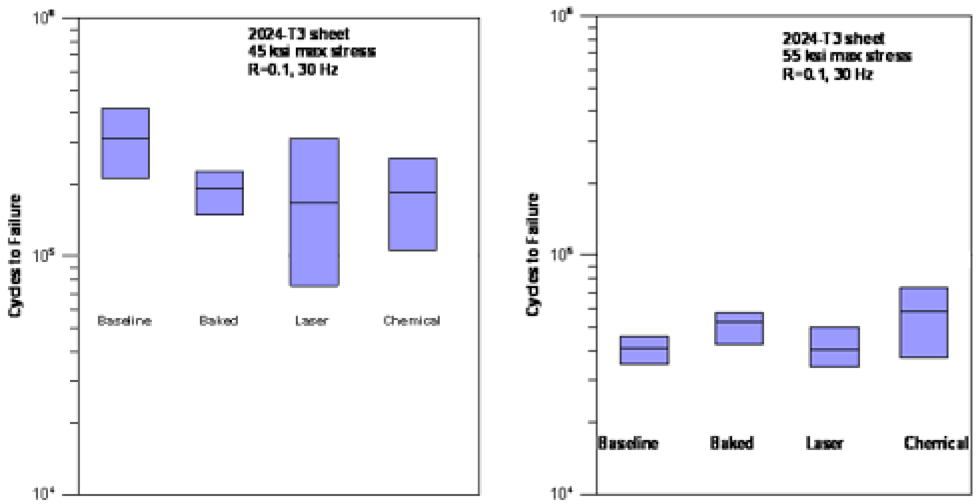


Figure 4. Smooth Fatigue Results of 2024 Aluminum Samples

A debit in fatigue life for the baked, unstripped samples as compared to the unprocessed baseline samples was documented at lower stress levels. These results show that in order to accurately assess the fatigue life effects caused by the depaint process itself the fatigue performance of a painted, aged, and stripped aluminum material should not be compared to a baseline unprocessed panel but, instead, to an unstripped material that has gone through the same thermal processes. For each stress condition that was tested, the resulting scatter bands in life for the laser and chemically stripped samples correspond with the baked baseline samples. This indicates that no debit in fatigue performance was caused by these two de-painting processes on 2024 aluminum.

The two stress levels that were selected for the smooth fatigue testing of the 7075 aluminum samples were 44 and 55 ksi. The test results are presented in **Table 13** and are graphically depicted in **Figure 5**.

Table 13. 7075 Aluminum Fatigue Data

Substrate	Removal Method	Max Stress ksi	Average Cycles to Failure	Maximum Cycles to Failure	Minimum Cycles to Failure
7075 Al Bare	None	44	93,904	135,276	46,533
		55	36,764	44,013	29,921
7075 Al Bare	None - Baked	44	118,372	201,395	33,400
		55	22,776	31,077	14,849
7075 Al Bare	Chemical	44	64,732	79,858	50,445
		55	31,320	40,058	26,847
7075 Al Bare	Laser	44	133,809	243,037	57,183
		55	32,421	43,518	24,529

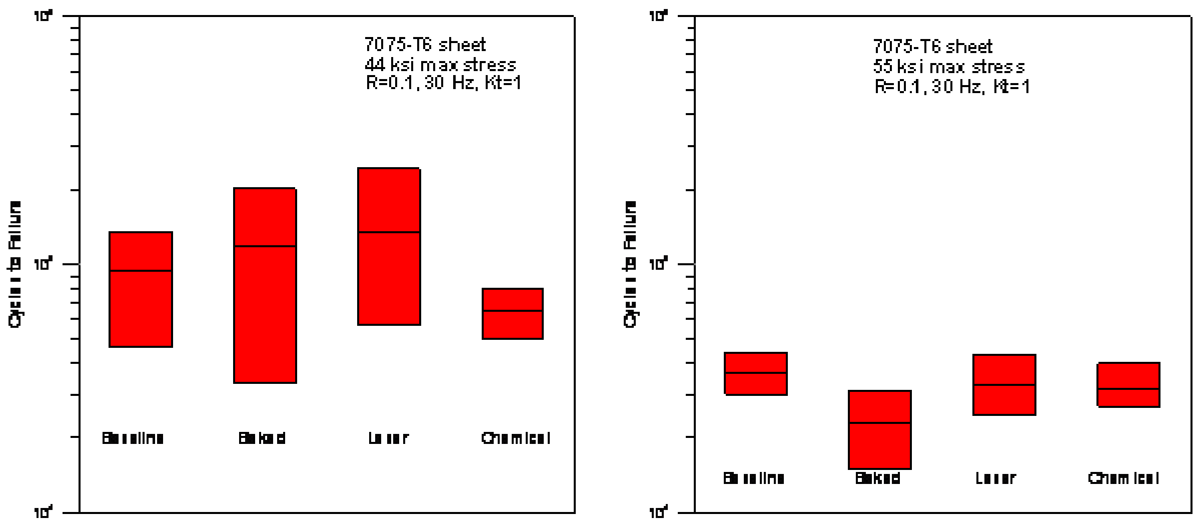


Figure 5. Smooth Fatigue Results of 7075 Aluminum Samples

As was demonstrated in the 2024 aluminum samples a debit in fatigue life is caused by the baking process, but no degradation in fatigue life is present when the laser and chemical stripping processes are compared to the baseline baked panels.

5.2 HONEYCOMB STRUCTURAL MATERIALS ASSESSMENT

Optimization testing was conducted prior to processing the test panels that were used for the honeycomb structural materials assessment. This optimization testing was focused on determining the proper settings of the system variables that allowed for maximum strip rate without causing damage to the substrate. Because the face sheets of these structures are extremely thin and are bonded to a honeycomb structure using adhesives, it was necessary to ensure that heat input was significantly less. As a result, system setting(s) were modified to ensure a much more conservative approach. The settings that were used throughout the honeycomb structural materials assessment are presented in **Table 14**.

Table 14. RLCRS Parameters Used for Aluminum Substrate Assessment

Units Measured	Value
Laser Power	6000 W
Laser Power at surface	4500 W
Focused Spot Size	0.7 mm x 4.5 mm ellipse
Irradiance	102.3 kW/cm^2
Scan Rate	7 m/s
Scan Width	127 mm
Stand-Off Distance	500 mm
Sweep Rate – 0.010 inch face sheet	3.0 in/s
Sweep Rate – 0.016 inch	2.5 in/s
Sweep Rate – alternate setting for both face sheet sizes	3.75 in/s

During testing of the peel strength of the honeycomb structures, it was discovered that a manufacturing defect was present in all of the samples. The manufacturer had not performed proper surface preparation of the face sheets prior to bonding to the honeycomb core. This caused adhesive failures in the baseline as well as the panels that had been subjected to coating removal operations. This manufacturing defect prevents any valid conclusions from being made from the results of the peel or flexural properties testing.

Because these test results were not valid, OC-ALC engineering personnel requested that testing of the maximum temperature that was reached on the back surface of the face sheet be conducted. The rationale of this test is that there are known temperatures at which the standard adhesives that are used in honeycomb structures will decompose. The engineering staff requested that the maximum temperature be kept under 180° F.

In order to meet this temperature requirement, a faster robot sweep rate was required to be developed. Because this alternate sweep rate was developed after the testing was completed, the test panels that were processed using the alternate strip rate were only subjected to one cycle of laser coating removal. Test panels that were processed using the other sweep rates were subjected to four coating removal cycles.

5.2.1 COATING STRIP RATE ON HONEYCOMB STRUCTURES

Trials were conducted to determine the rate at which each of the coating systems could be removed from the aluminum honeycomb structures. This test was performed for informational purposes only, and no JTP acceptance criterion was established. During the course of this strip rate testing, the coatings were completely stripped to the substrate. The coating strip rate test data that were compiled are based on coating removal from a test area equal to 3 ft^2. The test results are summarized in **Table 15**. The strip rate that is reported in this table considers the actual measured thickness of the coating and normalizes the rate to a 10-mil thick coating.

Table 15. Summary of Coating Strip Rate on a Honeycomb Structure

Substrate	Robotic Sweep Speed (inch/s)	Round 1 Strip Rate (ft^2/min)	Round 2 Strip Rate (ft^2/min)	Round 3 Strip Rate (ft^2/min)	Round 4 Strip Rate (ft^2/min)	AVERAGE STRIP RATE (ft^2/min)
Metallic Honeycomb 0.010 inch Face	3.0	0.8	0.9	0.9	0.7[a]	**0.9**
	3.75	1.1	-	-	-	**1.1**
Metallic Honeycomb 0.016 inch Face	2.5	0.9	0.9	1.0	0.8[a]	**0.9**
	3.75	1.1	-	-	-	**1.1**

a – the laser chiller was malfunctioning due to a refrigerant leak causing laser to lose power, data is invalid and not included in average strip rate calculation

5.2.2 VISUAL DAMAGE ASSESSMENT OF HONEYCOMB STRUCTURES

A visual examination at 10X magnification of the test panels for any indication of damage was performed. Substrate damage observations were conducted initially upon receiving the panels from the vendor and after each of the four removal cycles. Any surface abnormalities were noted and photographed. A summary of the visual examination is provided in **Table 16**.

Table 16. Visual Damage Assessment of Honeycomb Structures

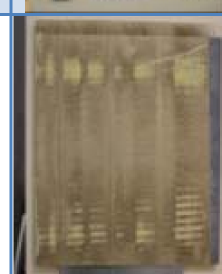
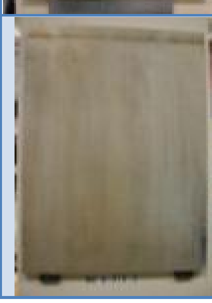
Substrate	Sweep Rate	Results	Typical Surface Picture (no magnification)
Metallic Honeycomb 0.01” Face	3.0 in/s	No surface abnormalities	
	3.75 in/s	No surface abnormalities	
Metallic Honeycomb 0.016” Face	2.5 in/s	No surface abnormalities	

Table 16. Visual Damage Assessment of Honeycomb Structures (continued)

Substrate	Sweep Rate	Results	Typical Surface Picture (no magnification)
	3.75 in/s	No surface abnormalities	

5.2.3 ULTRASONIC INSPECTION OF HONEYCOMB STRUCTURES

Ultrasonic testing was performed to assess possible degradation of the adhesive strength caused by high temperatures during the laser coating removal process. The aluminum honeycomb structures were examined by ultrasonic evaluations per ASTM E114, *Standard Practice for Ultrasonic Pulse-Echo Straight-Beam Examination by the Contact Method*, prior to laser or chemical stripping to ascertain the structural integrity of the test specimen and provide baseline data. The same panels were then ultrasonically examined after the first coating removal cycle and after the final coating removal cycle.

No discontinuities were discovered using the ultrasonic inspection on the baseline panels, chemically stripped panels, or laser stripped test panels.

5.2.4 PEEL RESISTANCE OF HONEYCOMB STRUCTURES

Peel resistance testing was performed to assess possible degradation of the adhesive bond between the face sheet and the aluminum honeycomb core caused by high temperatures during the laser coating removal process. This testing was performed using an Instron 4505 universal test machine following ASTM 1781, *Climbing Drum Peel for Adhesives*. Peeling loads were digitally recorded during the test to determine the average peel load, which was used to calculate the average peel torque. Five specimens were tested for each of the experimental conditions: unprocessed, baked four times, chemically stripped once, and laser stripped four times. As noted previously, the panels that were laser stripped using the 3.75 inch/s sweep rate were not tested. The average of the test results for the previously used sweep rate are summarized in **Table 17**.

Table 17. Peel Resistance of Honeycomb Structures

Removal Method	**Substrate**	**Average Peel Torque in-lbf/in *(std. dev.)***
None	Metallic Honeycomb - 0.010” Face	23.5 *(±1.95)*
	Metallic Honeycomb - 0.016” Face	27.9 *(±2.86)*
None - Baked	Metallic Honeycomb - 0.010” Face	22.8 *(±2.10)*
	Metallic Honeycomb - 0.016” Face	19.9 *(±1.86)*
Chemical	Metallic Honeycomb - 0.010” Face	25.6 *(±0.78)*
	Metallic Honeycomb - 0.016” Face	26.1 *(±2.85)*
Laser	Metallic Honeycomb - 0.010” Face	23.2 *(±1.10)*
	Metallic Honeycomb - 0.016” Face	27.2 *(±2.84)*

Following testing, an examination of the failed peeled surfaces showed that a defect in the manufacturing of the honeycomb structures was present. All of the test specimens showed that a lack of proper surface preparation prior to bonding the core structure to the face sheet led to adhesive failures, thereby invalidating peel results. A photograph of the failure is provided in **Figure 6**. Because of the original manufacturing defect, no conclusions can be reached regarding peel strength debit resulting from any of the depainting operations.

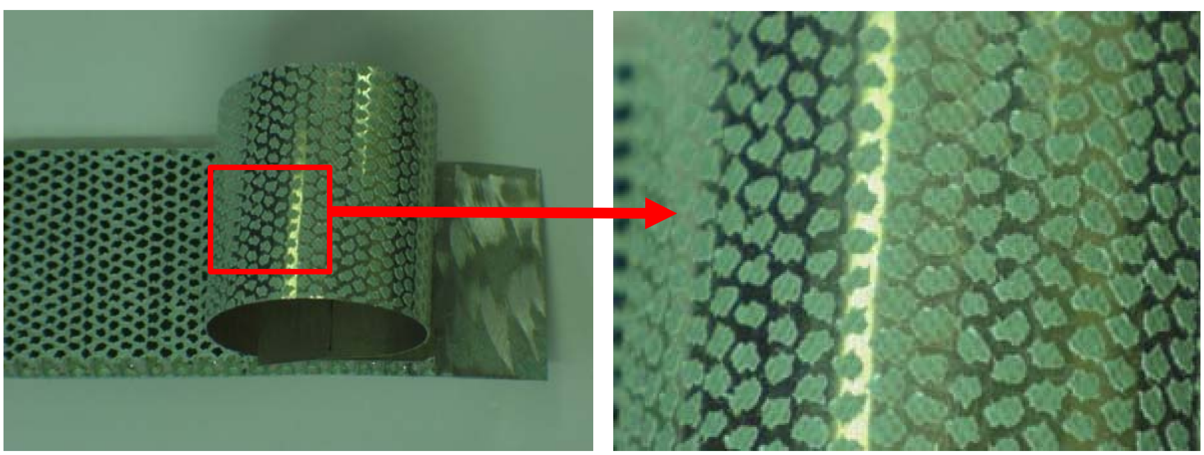


Figure 6. Peel Sample Showing Adhesive Failure

5.2.5 FLEXURAL PROPERTIES OF HONEYCOMB STRUCTURES

The flexural properties examination was performed to assess possible degradation of the honeycomb material caused by high temperatures during the laser coating removal process. Mechanical testing was conducted to assess the flexural properties of the sandwich construction using a long-beam flexure specimen according to MIL-STD-401, *Sandwich Constructions and Core Materials*, general Test Methods, which includes a reference to ASTM C393, *Standard Test Method for Flexural Properties of Sandwich Constructions*. Flexure testing of aluminum honeycomb specimens was performed using an Instron 4507 universal test machine using a 3-point loading mode. A photo showing the 3-point flexural test set-up is provided in **Figure 7**.

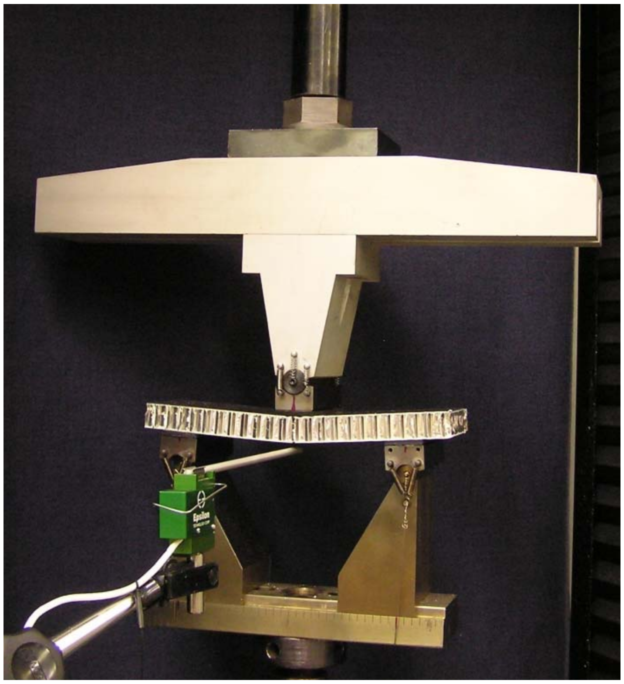


Figure 7. Flexural Testing Set-Up

The average of results of the 3-point flexural testing is provided in **Table 18**. It is important to note that all samples failed as a result of crushing of the honeycomb core, which resulted in an invalid core shear measurement. Therefore, it is not possible to judge whether any of the various depainting processes led to a loss in core shear strength.

Table 18. Flexural Testing of Honeycomb Structures

Removal Method	**Substrate**	**Average Peak Flexural Load lbf *(std. dev.)***
None	Metallic Honeycomb - 0.010" Face	950 *(±37.9)*
	Metallic Honeycomb - 0.016" Face	1447 *(±24.9)*
None - Baked	Metallic Honeycomb - 0.010" Face	1172 *(±33.1)*
	Metallic Honeycomb - 0.016" Face	1557 *(±60.7)*
Chemical	Metallic Honeycomb - 0.010" Face	986 *(±9.2)*
	Metallic Honeycomb - 0.016" Face	1436 *(±30.7)*
Laser	Metallic Honeycomb - 0.010" Face	1267 *(±202.4)*
	Metallic Honeycomb - 0.016" Face	1202 *(±229.0)*

5.2.6 DETERMINATION OF SUBSTRATE TEMPERATURE: HONEYCOMB STRUCTURES

Because manufacturing defects with the honeycomb structures led to inconclusive peel strength and flexural data, an additional test was requested to be added by OC-ALC personnel. This test involved determination of the maximum temperature that was reached on the back surface of the face sheet. In order to perform this test, one inch squares were removed from the honeycomb structure at locations across the test panel to provide access for thermocouples

to be attached to the back side of the face sheet. Care was taken during this procedure to ensure that all adhesive was removed from the back side of the face sheet so that the temperature reading would be as accurate as possible. A picture of the location of the thermocouple reading areas and a close up of these areas is provided in **Figure 8**.

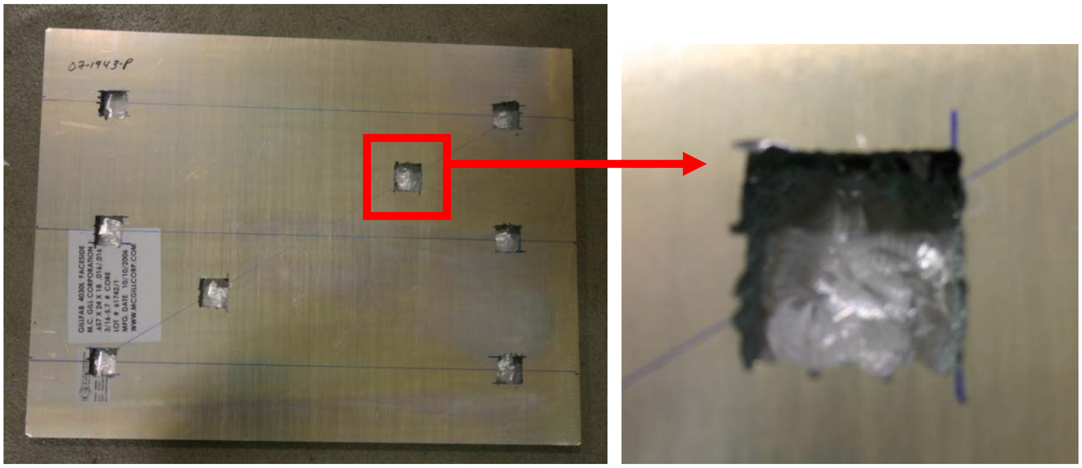


Figure 8. Preparation of Honeycomb Structure for Temperature Measurement

Eight Type K thermocouples were adhered to the back of the face sheet, and the panel was stripped using the 3.75 inch/s sweep speed. Temperature data were collected 100 times a second during the laser stripping operations. According to information received from OC-ALC, the acceptance criterion for this test was a maximum temperature spike of 180° F. The maximum recorded temperature when stripping the honeycomb structure with a 0.010 inch face sheet was 161° F. The maximum recorded temperature for the honeycomb structure with a 0.016 inch face sheet was 160° F. Graphs of the temperature readings for both of these structures are provided in **Figures 9** and **10**.

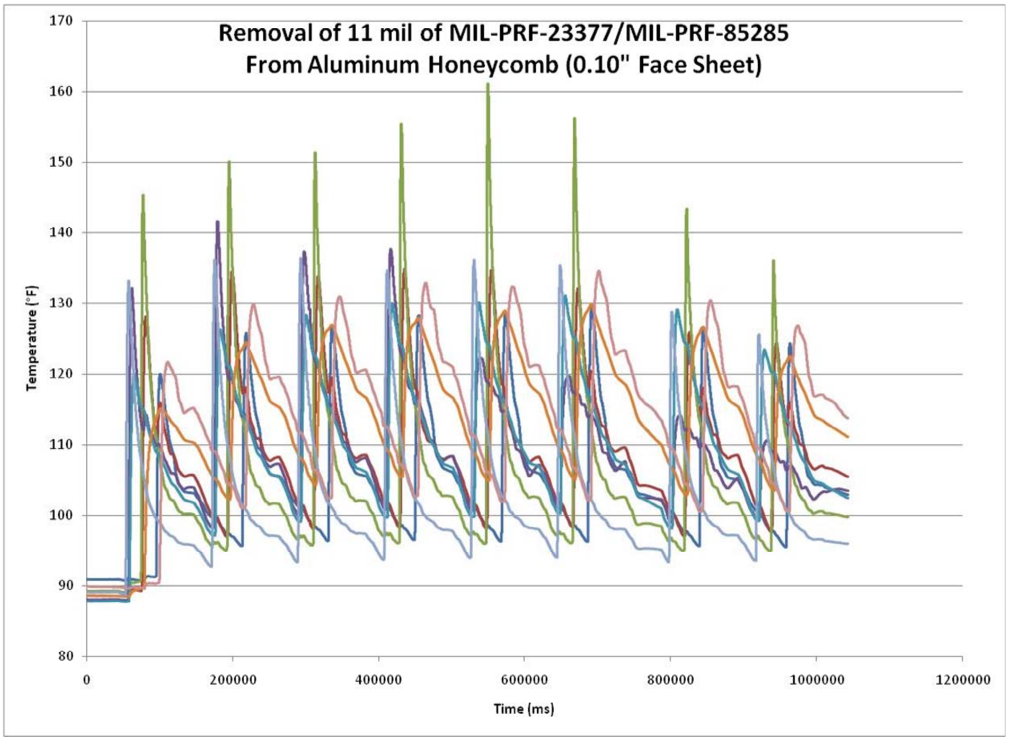


Figure 9. Temperature Readings for Honeycomb Structure: 0.010 Inch Face Sheet

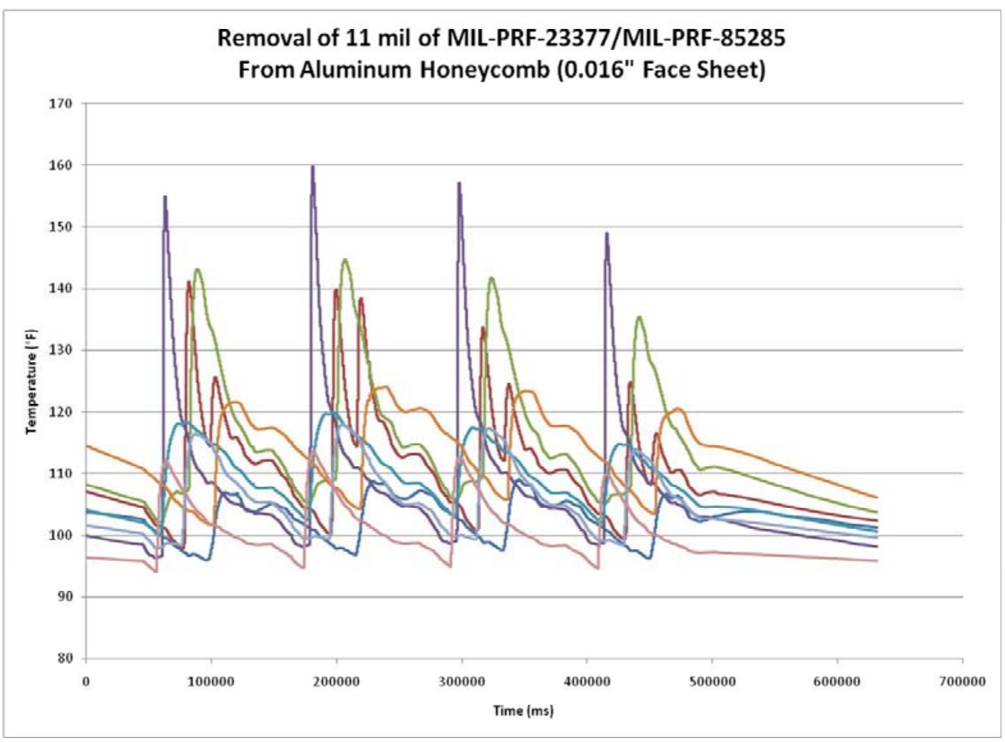


Figure 10. Temperature Readings for Honeycomb Structure: 0.016 Inch Face Sheet

6.0 DEMONSTRATION TEST RESULTS

Upon completing the screening testing, the RLCRS system was transitioned to OC-ALC, and demonstration testing was performed on actual aircraft parts. An overview of the demonstration tests that were conducted is presented in Table 19. A description of each of the test procedures that were followed, the testing methodologies, and a discussion of each test result are provided in the following sections.

Table 19. Demonstration Testing Overview

Performance Criteria	Laser Strip				
	Landing Gear Door	Rudder	Outboard Flap	Elevator	Outboard Aileron
Coating Strip Rate (ft^2/min)	1.53 (~2.6 mils)	1.12 (~6.1 mils)	1.86 (~3.4 mils)	1.86 (~3.6 mils)	2.03 (~3.4 mils)
Coating Strip Rate per mil coating removed (ft^2*mil/min)	3.97	6.81	6.33	6.79	7.41
Visual (Warping/Denting)	No	No/Yes*	No	No	No
Maximum Substrate Temperatures (°F)	Not recorded	Not recorded	Not recorded	Not recorded	Not recorded

* The rudder had one section of the part that was a magnesium substrate. This substrate was not one of the substrates that had been identified for this project; therefore, no optimized laser parameters had been developed for safe processing on magnesium. As a result, the magnesium panel did incur warping. Because there is currently no laser operating parameters for magnesium substrates that will not damage the substrate, a procedure for operators to check for the presence of magnesium prior to processing a part has been established.

The JTP called for substrate temperature to be recorded during demonstration testing, but it was discovered that this was not feasible without modifying the various aircraft parts due to their shape and construction. Because extensive temperature monitoring was performed during the screening testing, it was decided to omit the temperature evaluation on the actual parts.

All parts that were processed during this demonstration were moved, positioned, and processed by OC-ALC who had been previously trained on the operation of the RLCRS. CTC personnel attended this demonstration, provided guidance as to the most advantageous processing scheme for each part, and recorded all processing data.

6.1 KC-135 LANDING GEAR DOOR

The first production part that was selected for this demonstration was the KC-135 Landing Gear Door. For the purposes of this demonstration, a condemned Landing Gear Door was obtained. The two outside surfaces of the door were selected as candidate surfaces for processing using the RLCRS system. These two part surfaces were previously processed by OC-ALC using the automated high pressure water system that was recently disapproved by the KC-135 Program Office. Only the two outside surfaces were stripped using the water jet system due to the complex geometry that exists on the interior surfaces. Interior surfaces were depainted using chemical stripping agents.

Pictures of the landing gear door prior to laser treatment are provided in **Figure 11**. The coating that was on this part was measured to be between 2.2 to 3.2 mils thick (average thickness measured was 2.6 mils). Because this was an old, condemned part, the coating formulation was unknown, but it was observed to be a gray coating that was severely aged and weathered. Additionally, this part was heavily covered with dirt and grease.

Figure 11. Landing Gear Door Prior To Laser Stripping

The part was measured, and a dimensional diagram of the part was produced. This drawing was then imported into a solid modeling program in order to accurately calculate the total surface area of the part. This diagram is provided in **Figure 12**. Total surface area that was present on the outside surfaces was determined to be 57 ft^2 with a total part surface area, including the inner surfaces and ends, of 126 ft^2. Most of the internal surface area present on the inner surfaces could potentially be stripped using the laser if the wheel indentations were masked off.

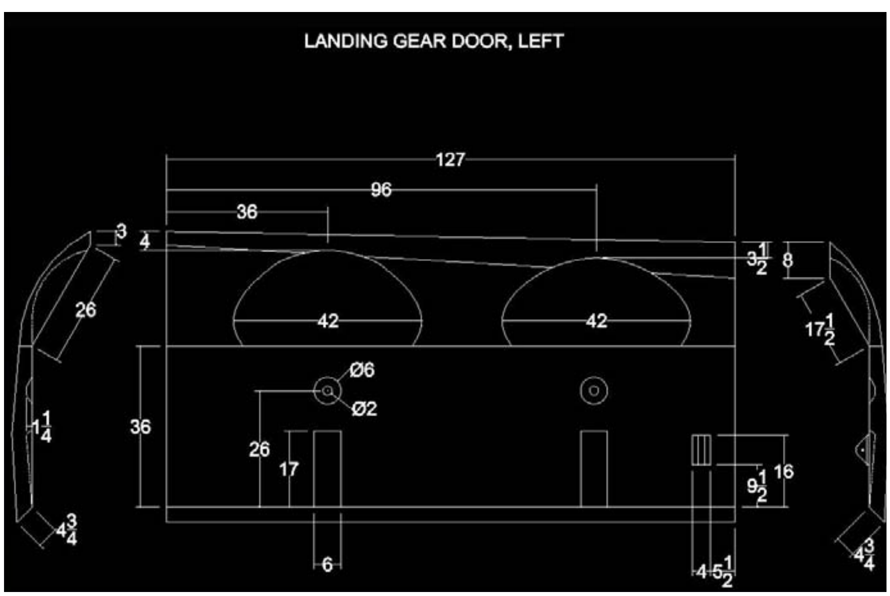


Figure 12. Dimensional Drawing of KC-135 Landing Gear Door

Due to the limitations of the RLCRS operating envelope, the landing gear door was processed by first stripping Surface One, and, then, opening the door and laying Surface Two flat on the parts cart (as shown in Figures 1 and 2). No masking was required for this part, and no cleaning or removal of surface contaminants was performed prior to laser processing. Surfaces One and Two were completely stripped by the RLCRS. No attempt was made to process the two inner surfaces. Details of the parameters that were used during laser stripping are provided in **Table 20.**

Table 20. Laser Parameters Used for KC-135 Landing Gear Door

Units Measured	Value
Laser Power	6000 W
Laser Power at surface	4500 W
Focused Spot Size	0.7 mm x 4.5 mm ellipse
Irradiance	102.3 kW/cm^2
Scan Rate	7 m/s
Scan Width	127 mm
Stand-Off	500 mm
Sweep Rate	2.75 in/s
Path Overlap	1 in

This part took 5 minutes to initially position on the parts cart and prepare for stripping. Surface One was stripped in 39 minutes. The part was then repositioned for processing of Surface Two. This repositioning took 6 minutes. Surface Two was then stripped in 49 minutes. All of these actions totaled 99 minutes to completely process the outside surfaces of this part. Pictures of the stripped surfaces are provided in **Figure 13**.

Figure 13. KC-135 Landing Gear Door after Processing Using the RLCRS

The stripped surfaces of the part were completely free from coating and showed no visual indications of damage. The two surfaces that were stripped during this demonstration were in a suitable condition to be sent for repainting after washing. The calculated results of this testing, including coating removal rate, fluence, and strippable area assessment, are detailed in **Table 21**.

Table 21. Results for Assessment of KC-135 Landing Gear Door

Parameter	Value
Coating Thickness	2.6 mils
Number of Stripping Passes	3
Total Process Time (including set-up/masking/etc.)	99 minutes
Surface Area Stripped	56.89 ft^2
Total Fluence	152.18 J/cm^2
Coating Removal Rate	1.53 ft^2/min
Coating Removal Rate Per mil Coating Removed	3.97 ft^2-mil/min
Total Part Processing Rate	0.57 ft^2/min
Strippable Area	45% of total surface area

6.2 KC-135 RUDDER

A condemned KC-135 rudder was obtained and used for the second part demonstration. Pictures of the part prior to laser treatment are provided in **Figure 14**. The coating that was present on this part was measured to be 4.5 to 8.2 mils thick (average of measurements is 6.1 mils). The paint system present on this part was not identified, but it consisted of a severely aged white topcoat and a green primer. Also present on the part surface were black and yellow striping as well as, several instances of lettering.

Figure 14. KC-135 Rudder Prior to Laser Stripping

As was done with the landing gear door, the part was measured, and a dimensional solid model of the part was produced in order to determine the total surface area requiring stripping. A diagram of the drawing that was produced is provided in **Figure 15**. The total surface area of the part, including both ends and sides, was approximately 245 ft^2. Approximately 200 ft^2 of this surface area was accessible for coatings removal by the RLCRS.

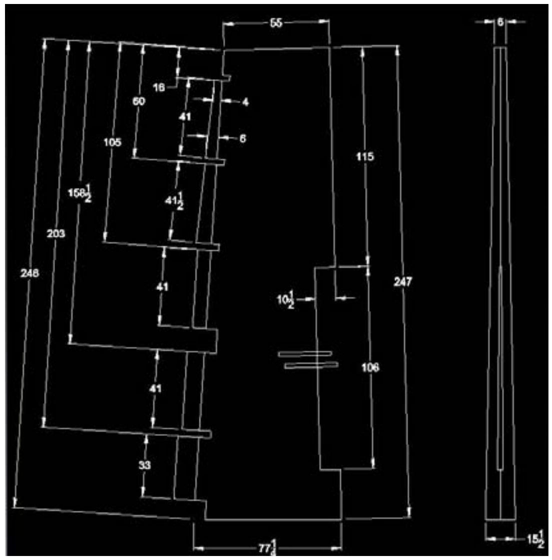


Figure15. Dimensional Drawing of KC-135 Rudder

Due to the large size and weight of this part, initial placement of it on the parts cart took slightly longer than the other parts. In total, 15 minutes were spent moving the part from its trailer to the cart and masking three small areas on the surface. This part was able to be processed by the RLCRS system by staging each side through 3 positions along its length. Movement of the part to each of these sections was accomplished using the RLCRS's semi-automated parts cart. Details of the parameters that were used during laser stripping are provided in **Table 22**.

Table 22. Laser Parameters Used for KC-135 Rudder

Units Measured	Value
Laser Power	6000 W
Laser Power at surface	4500 W
Focused Spot Size	0.7 mm x 4.5 mm ellipse
Irradiance	102.3 kW/cm^2
Scan Rate	7 m/s
Scan Width	127 mm
Stand-Off	500 mm
Sweep Rate	2.75 in/s
Path Overlap	0.125 in

It took six passes and 180 minutes to strip the coating from each side of the rudder. In total, 390 minutes were spent preparing and processing this part. The coating on this part was difficult to remove and atypical for what is usually processed at OC-ALC. When a typical coating is encountered, this time is expected to be reduced. Pictures of the stripped surfaces are provided in **Figure 16**.

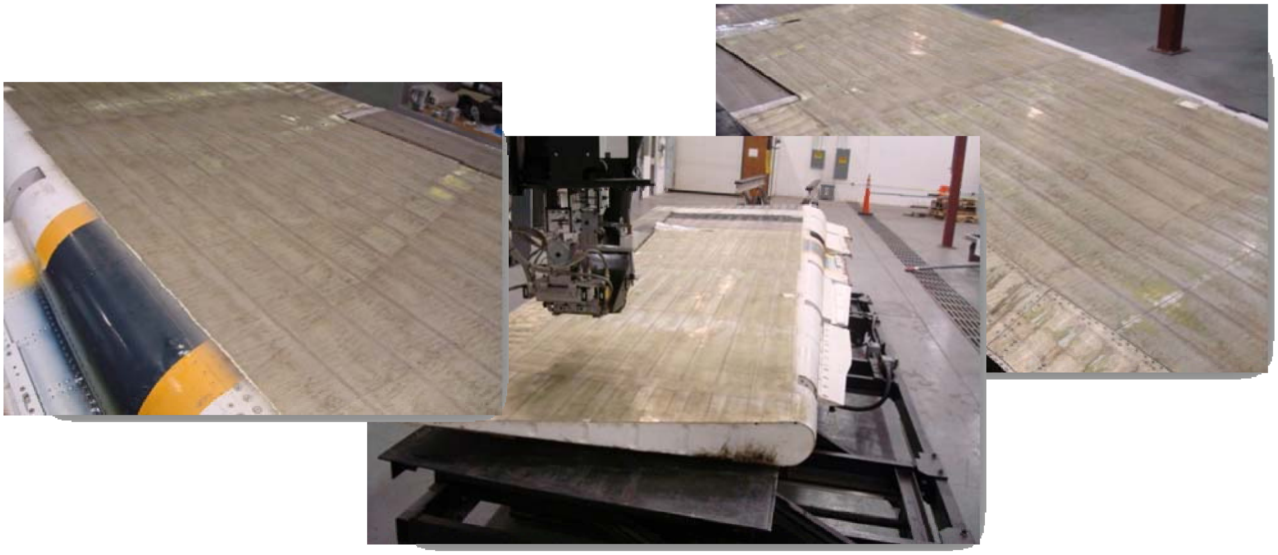


Figure 16. KC-135 Rudder After Processing Using the RLCRS

A small amount of primer was left in the areas where the striping and lettering was present. A decision was made to leave these small areas to be stripped using the handheld lasers as part of touch-up operations instead of performing a sixth pass over the entire surface.

During stripping of the rudder it became apparent that one section of the part was made of a different substrate than aluminum. After stripping was completed, it was revealed that this section was a magnesium substrate. Conversations with the operators and OC-ALC personnel revealed that this substrate is found occasionally on the different parts that are processed. This substrate is not one of the substrates that had been identified for this project, so no optimized laser parameters had been developed for safe processing on magnesium. A picture of the substrate after processing using the current parameters is provided in **Figure 17**.

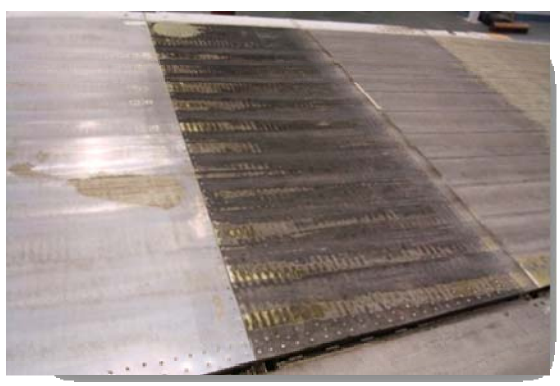


Figure 17. Detail of Damage to Magnesium Substrate

Because it is not known if this substrate will be encountered prior to processing, a method for determining its presence is needed. AFRL Non-Destructive Inspection (NDI) personnel have advised the project team that detection of magnesium can be accomplished using an eddy current conductivity meter. Because there are currently no laser operating parameters for

magnesium substrates that will not damage the substrate, it is recommended that RLCRS operators take conductivity measurements of the main sections of the parts prior to processing. Sections that are found to have a magnesium substrate can be masked or the entire part can be routed to traditional chemical stripping areas. Details of the full set of calculated results for the demonstration of the KC-135 rudder are provided in **Table 23**.

Table 23. Results for Assessment of KC-135 Rudder

Parameter	VALUE
Coating Thickness	6.1 mils
Number of Stripping Passes	5
Total Process Time (including set-up/masking/etc.)	390 minutes
Surface Area Stripped	201.60 ft^2
Total Fluence	253.64 J/cm^2
Coating Removal Rate	1.12 ft^2/min
Coating Removal Rate Per mil Coating Removed	6.81 ft^2-mil/min
Total Part Processing Rate	0.52 ft^2/min
Strippable Area	82% of total surface area

6.3 KC-135 ELEVATOR

The next part that was processed was a condemned KC-135 elevator. Pictures of the part prior to laser treatment are provided in **Figure 18**. The coating on this part was measured to be 2.5 to 5.4 mils thick (average of measurements is 3.65 mils). The paint system was the standard MIL-PRF-23377 primer and MIL-PRF-85285 topcoat that is normally applied to these parts at OC-ALC. This part had been recently painted by OC-ALC.

Figure 18. KC-135 Elevator Prior To Laser Stripping

The flap was measured, and a dimensional solid model of the part was produced in order to determine the total surface area requiring stripping. A diagram of the drawing that was produced is provided in **Figure 19**. Total surface area of the part including both ends and sides is approximately 154 ft^2. Approximately 126 ft^2 of this surface area was accessible for coatings removal by the RLCRS.

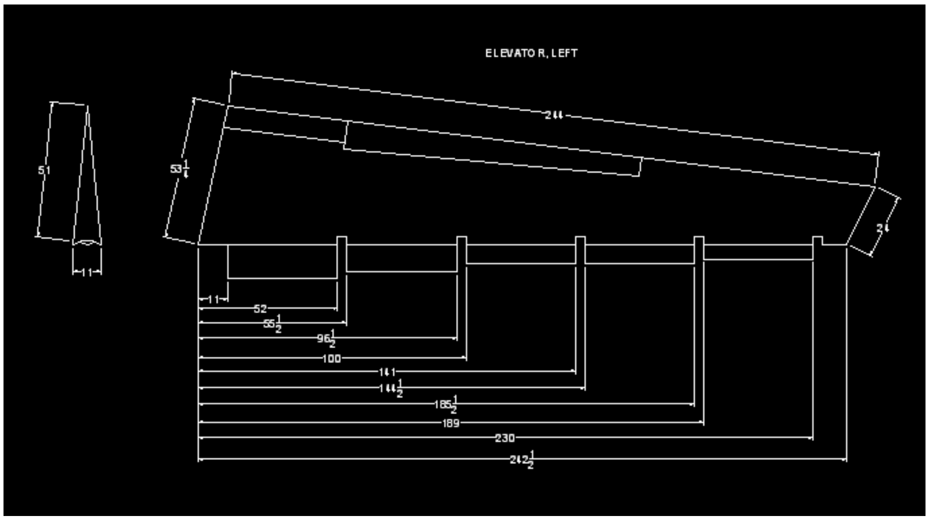


Figure 19. Dimensional Drawing of KC-135 Elevator

Use of the overhead crane was required to move the elevator from its storage trailer and position it on the parts cart. In total, 10 minutes were spent preparing this part for processing. This part was able to be processed by the RLCRS system by staging each side through 3 positions along its length. Movement of the part to each of these sections was accomplished using the semi-automated parts cart. Details of the system parameters that were used during processing of the part are provided in **Table 24**.

Table 24. Laser Parameters Used for KC-135 Elevator

Units Measured	Value
Laser Power	6000 W
Laser Power at surface	4500 W
Focused Spot Size	0.7 mm x 4.5 mm ellipse
Irradiance	102.3 kW/cm^2
Scan Rate	7 m/s
Scan Width	127 mm
Stand-Off	500 mm
Sweep Rate	2.75 in/s
Path Overlap	0.125 in

Laser stripping of the KC-135 elevator took 3 passes for each section and totaled 79 minutes for each side. When the positioning and masking steps are included, the part took a total of 173 minutes to process. Pictures of the stripped surfaces are provided in **Figure 20**.

Figure 20. KC-135 Elevator After Processing Using the RLCRS

The stripped surfaces of the part were completely free from coating and showed no visual indications of damage. The calculated results of this demonstration are detailed in **Table 25**.

Table 25. Results for Assessment of KC-135 Elevator

Parameter	Value
Coating Thickness	3.65 mils
Number of Stripping Passes	3
Total Process Time (including set-up/masking/etc.)	173
Surface Area Stripped	126.00 ft^2
Total Fluence	152.18 J/cm^2
Coating Removal Rate	1.86 ft^2/min
Coating Removal Rate Per mil Coating Removed	6.79 ft^2-mil/min
Total Part Processing Rate	0.73 ft^2/min
Strippable Area	82% of total surface area

6.4 KC-135 OUTBOARD AILERON

Several condemned KC-135 Outboard Ailerons were available for processing. The ailerons are constructed of a thin-skinned aluminum honeycomb, and one of the available ailerons showed visible signs of delamination of the facesheet from the honeycomb core. Because of this defect, this part was not processed as part of the demonstration. The second outboard aileron that was available showed no visible signs of damage. Pictures of the part prior to laser treatment are provided in **Figure 21**. The coating that was on this part was measured to be 2.86 to 4.13 mils thick (average of measurements is 3.44 mils). The paint system was the standard MIL-PRF-23377 primer and MIL-PRF-85285 topcoat that is normally applied to these parts at OC-ALC. This part had been recently painted by OC-ALC.

Figure 21. KC-135 Outboard Aileron Prior To Laser Stripping

The aileron was measured, and a dimensional solid model of the part was produced in order to determine the total surface area requiring stripping. The drawing that was produced is provided in **Figure 22**. Total surface area of the part, including both ends and sides, is approximately 106 ft^2. Approximately 77 ft^2 of this surface area was accessible for coatings removal by the RLCRS.

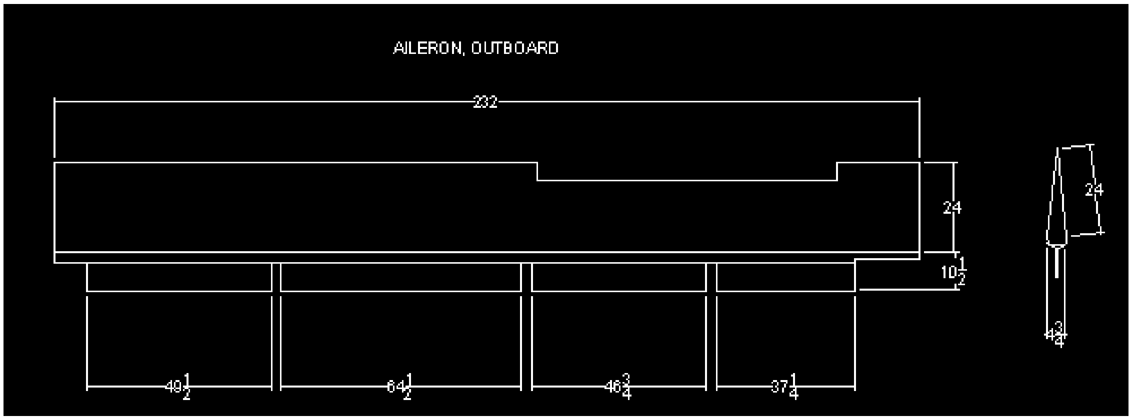


Figure 22. Dimensional Drawing of KC-135 Outboard Aileron

Use of the overhead crane was required to move the aileron from its trailer and position it on the parts cart. In total, 10 minutes were spent preparing this part for processing. This part was able to be processed by the RLCRS system by staging each side through 3 positions along its length. Movement of the part to each of these sections was accomplished using the semi-automated parts cart. Details of the parameters that were used during processing of the part are provided in **Table 26**.

Table 26. Laser Parameters Used for Outboard Aileron

Units Measured	Value
Laser Power	6000 W
Laser Power at surface	4500 W
Focused Spot Size	0.7 mm x 4.5 mm ellipse
Irradiance	102.3 kW/cm^2
Scan Rate	7 m/s
Scan Width	127 mm
Stand-Off	500 mm
Sweep Rate	3.00 in/s
Path Overlap	0.125 in

Laser stripping of the outboard aileron took 3 passes for each section and totaled 55 minutes for each side. When the positioning and masking steps are included, the part took a total of 120 minutes to process. Pictures of the stripped surfaces are provided in **Figure 23**.

Figure 23. KC-135 Outboard Aileron after Processing Using the RLCRS

The stripped surfaces of the part were completely free from coating and showed no visual indications of damage. The calculated results of this demonstration are detailed in **Table 27**.

Table 27. Results for Assessment of KC-135 Outboard Aileron

Parameter	Value
Coating Thickness (mils)	3.44 mils
Number of Stripping Passes	3
Total Process Time (min) (including set-up/masking/etc.)	120 minutes
Surface Area Stripped (ft^2)	77 ft^2
Total Fluence (J/cm^2)	139.5 J/cm^2
Coating Removal Rate (ft^2/min)	2.03 ft^2/min
Coating Removal Rate Per mil Coating Removed (ft^2 mil/min)	7.41 ft^2-mil/min
Total Part Processing Rate (ft^2/min)	0.64 ft^2/min
Strippable Area (% of surface area stripped)	73% of total surface area

6.5 KC-135 OUTBOARD FLAP

The final part that was processed during the demonstration testing was a KC-135 Outboard Flap. This part was not an ideal candidate for processing using the RLCRS because there are obstructions on the leading edge of the part and the inside radius is smaller than the RLCRS workhead. The flap does have a fairly large surface area that can be processed, so it is possible

that OC-ALC may decide to process this part using the RLCRS combined with other stripping methods.

As with the other parts processed, a condemned flap was obtained and processed. Pictures of the part prior to laser treatment are provided in **Figure 24**. The coating that was on this part was measured to be 2.8 to 3.7 mils thick (average of the thicknesses measured was 3.4 mils). The paint system on this part was not identified, but it consisted of an aged gray topcoat and no primer.

Figure 24. KC-135 Outboard Flap Prior To Laser Stripping

The flap was measured, and a dimensional solid model of the part was produced in order to determine the total surface area requiring stripping. A diagram of the drawing that was produced is provided in **Figure 25**. The total surface area of the part including both ends and sides is approximately 182 ft^2. Approximately 120 ft^2 of this surface area was accessible for coatings removal by the RLCRS.

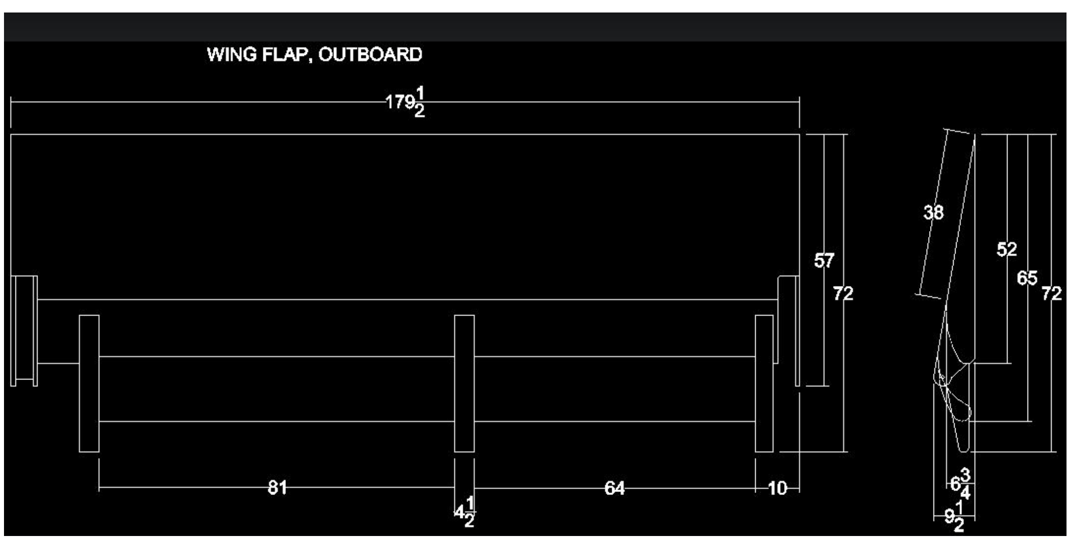


Figure 25. Dimensional Drawing of KC-135 Outboard Flap

This part is not overly large, but it is heavy. Because of its weight, the use of the overhead crane was required to move the flap from its storage trailer and position it on the parts cart. In

total, 10 minutes were spent preparing for processing. This part was able to be processed by the RLCRS system by staging each side through 2 positions along its length. Movement of the part to each of these sections was accomplished using the semi-automated parts cart. Details of the laser parameters that were used during processing of the part are provided in **Table 28**.

Table 28. Laser Parameters Used for Outboard Flap

Units Measured	Value
Laser Power	6000 W
Laser Power at surface	4500 W
Focused Spot Size	0.7 mm x 4.5 mm ellipse
Irradiance	102.3 kW/cm^2
Scan Rate	7 m/s
Scan Width	127 mm
Stand-Off	500 mm
Sweep Rate	2.75 in/s
Path Overlap	0.125 in

Laser stripping of this part took 3 passes for each section and totaled 65 minutes for each side. When the positioning and masking steps are included, the part took a total of 140 minutes to process. Pictures of the stripped surfaces are provided in **Figure 26**.

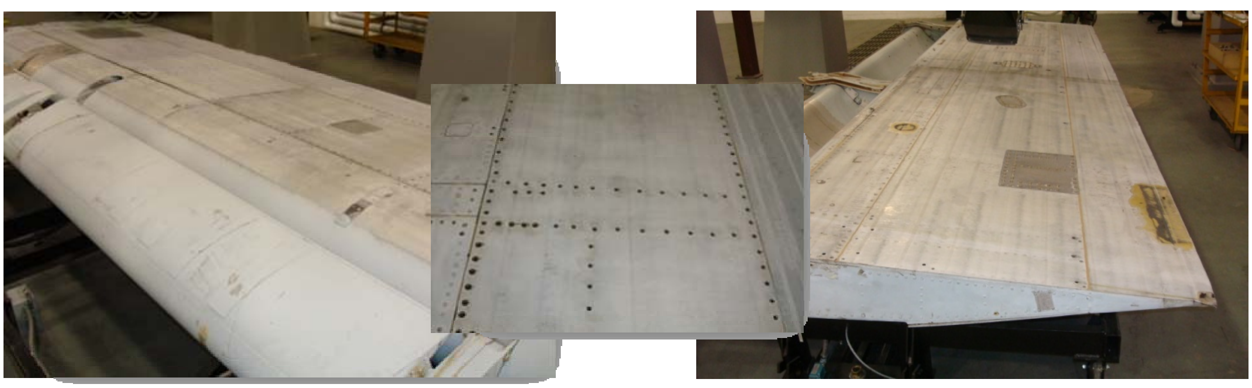


Figure 26. KC-135 Outboard Flap after Processing Using the RLCRS

The stripped surfaces of the outboard flap were completely free from coating and showed no visual indications of damage. It would be possible to increase the surface area stripped on the top side of the part by constructing a small amount of flashing between the leading edge and the main body of the part. This would enable the system to process the concave area in front of the part. The calculated results of this demonstration are detailed in **Table 29**.

Table 2. Results for Assessment of KC-135 Outboard Flap

Parameter	Value
Coating Thickness	3.4 mils
Number of Stripping Passes	3
Total Process Time (including set-up/masking/etc.)	140 minutes
Surface Area Stripped	120.00 ft^2
Total Fluence	152.18 J/cm^2
Coating Removal Rate	1.86 ft^2/min
Coating Removal Rate Per mil Coating Removed	6.33 ft^2-mil/min
Total Part Processing Rate	0.86 ft^2/min
Strippable Area	49% of total surface area

7.0 SUMMARY AND RECOMMENDATIONS

This testing was conducted in order to validate the use of the RLCRS for use in coatings removal operations on large components that are removed from aircraft during depot maintenance. Use of this technology would reduce or eliminate DoD dependence on the hazardous chemicals and processes that are currently used to remove coatings. The chemicals that are typically used in this process are high in VOCs and HAPs, which are targeted for reduction/elimination by environmental regulations.

The objective of the screening testing was to verify the ability of the RLCRS to effectively remove common DoD coating systems without causing physical damage to the substrate. The results from this testing provide the DoD with information that can be used to assist in the implementation of laser paint stripping operations at their facilities. The objective of the demonstration testing was to verify the ability of the RLCRS to effectively process the parts that are encountered during depot maintenance operations.

Screening test results indicated that use of the RLCRS has no detrimental effect on 2024 and 7075 aluminum substrates. All testing that was performed on these substrates including superficial hardness, conductivity, tensile testing, and fatigue life showed no degradation in material properties from baseline conditions.

The screening test results show that use of the RLCRS on honeycomb structures causes no detectible defects when visually examined and subjected to ultrasonic inspection. Additionally, the testing showed that the backside of the honeycomb face sheet will not be exposed to temperatures greater than 161° F during processing when the RLCRS is operated at a robotic sweep speed of 3.75 inch/second. Due to defects in the manufacturing of the honeycomb structural test materials comparisons in the effects of the RLCRS on peel resistance and flexural properties cannot be made. It is recommended that additional honeycomb structural test materials be procured and this testing be repeated.

Results from the demonstration testing show that the RLCRS can effectively process a wide variety of parts that are encountered at OC-ALC. The RLCRS system was able to efficiently remove coatings from all of the condemned parts that were processed without causing damage.